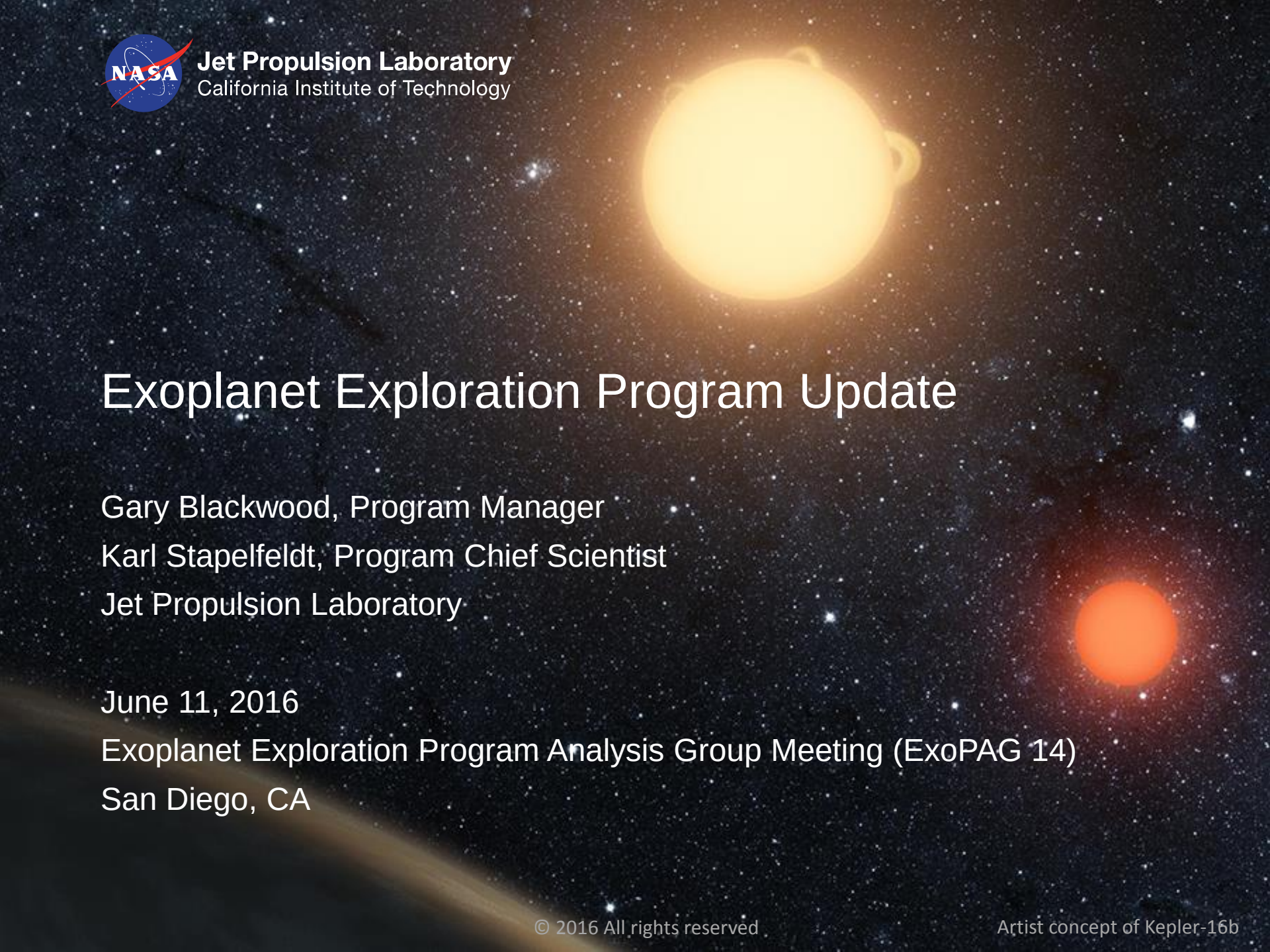


Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program Update

Gary Blackwood, Program Manager
Karl Stapelfeldt, Program Chief Scientist
Jet Propulsion Laboratory

June 11, 2016
Exoplanet Exploration Program Analysis Group Meeting (ExoPAG 14)
San Diego, CA

Artist concept of Kepler-16b

NASA Exoplanet Exploration Program

NASA Astrophysics Division, Science Mission Directorate

Purpose described in 2014 NASA Science Plan

1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

The Search for Exoplanets is…
The Search for Life in our Galaxy

ExEP serves the science community and NASA APD by Implementing NASA's space science vision for exoplanets

http://exep.jpl.nasa.gov

NASA Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler, K2

WFIRST

Starshade

Decadal Studies

Coronagraph

Public Communications

Supporting Research & Technology

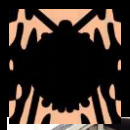
Key Sustaining Research

Large Binocular Telescope Interferometer

Keck Single Aperture Imaging and RV

NN-EXPLORE

Technology Development



Coronagraph Masks

High-Contrast Imaging

Deployable Starshades

NASA Exoplanet Science Institute

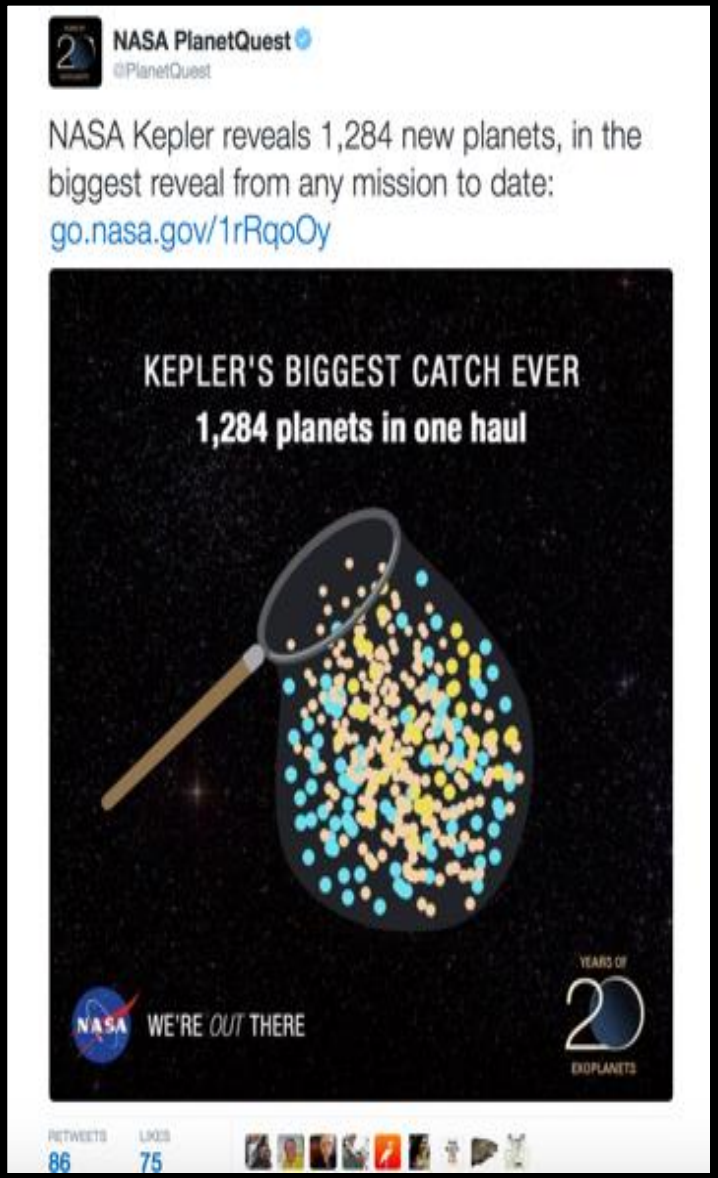
Archives, Tools, Sagan Fellowships, Professional Engagement

http://exep.jpl.nasa.gov

Kepler Close Out

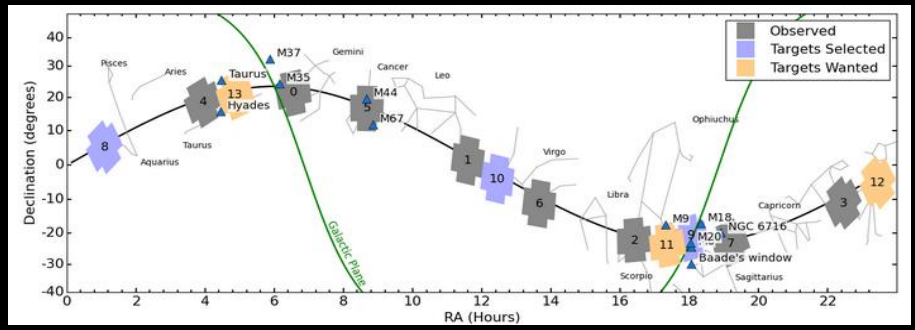
Delivering Kepler's Legacy

- Kepler closeout and final data processing continues steadily within overall schedule margin
  - SOC 9.3 Q0-Q17 Short Cadence Light Curves Delivered to MAST (June 2016, imminent)
  - Documentation Completeness Review (Oct 2016)
  - SOC 9.3 Final Occurrence Rate Products (April 2017)

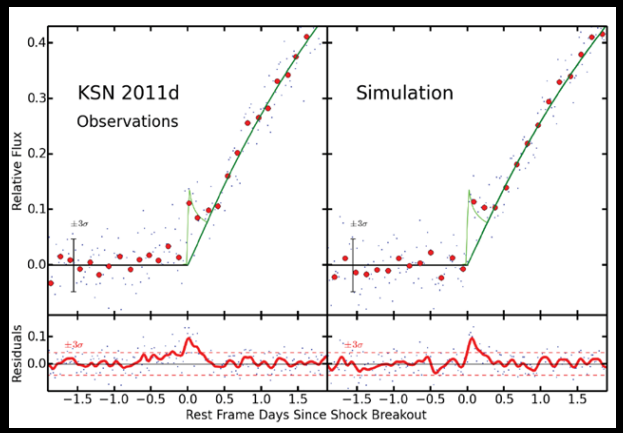


Kepler K2

Extending Kepler to the Ecliptic



- Since last ExoPAG:
  - Data released through Campaign 7 (Campaign 8 imminent)
- High-value exoplanets: small, rocky, nearby (46 pc), orbiting bright stars.
- Spacecraft fully operational after suspension of operations April 8-22 (SEU requiring resets of onboard systems)
- Campaign 9 (Microlensing) was slightly truncated, first 28 days of data are on the ground. NASA funding UKIRT time.
- K2 does much more than exoplanets - example: shock breakout seen in supernova lightcurve (Garnavich et al. 2016)



https://exep.jpl.nasa.gov/k2/

Progress towards 2010 Decadal Survey Priorities

Program Updates

Preparations for 2020 Decadal Survey

Welcome Kendra Short

Deputy Program Manager

Exoplanet Exploration

Welcome Dr. Karl Stapelfeldt

Program Chief Scientist

Exoplanet Exploration

Progress towards 2010 Decadal Survey Priorities

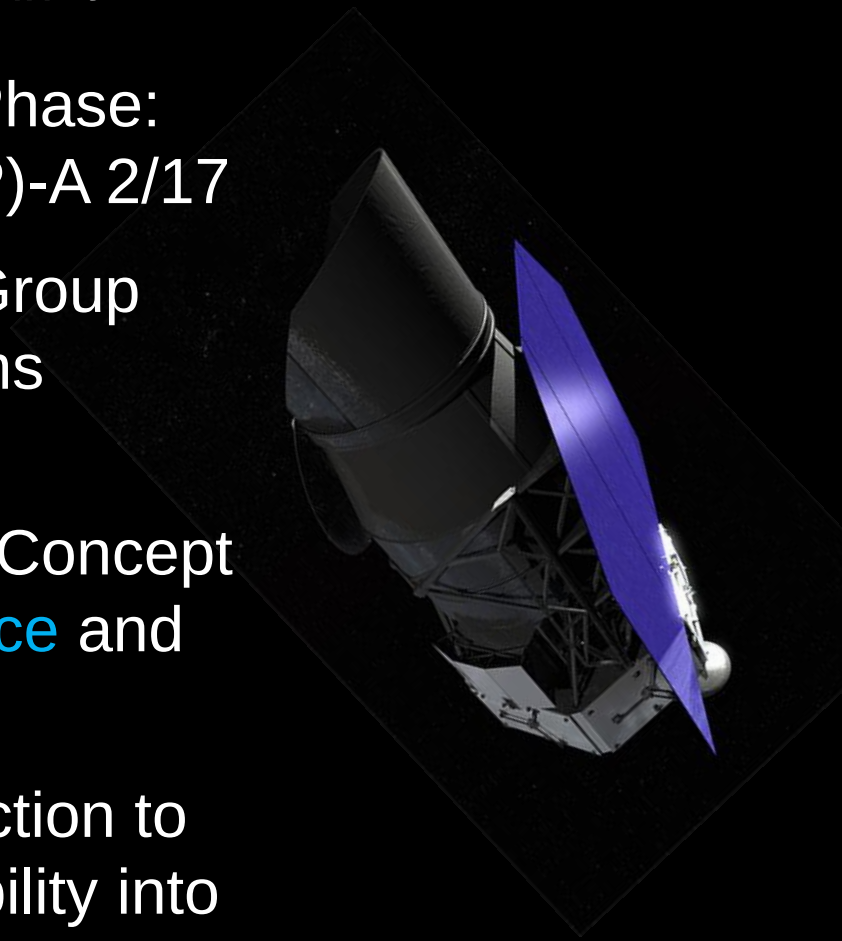
Program Updates

Preparations for 2020 Decadal Survey

WFIRST

The Fate of the Universe, and Our Place in It

- WFIRST entered Formulation Phase: NASA Key Decision Point (KDP)-A 2/17
- Formulation Science Working Group and Science Investigation Teams underway
- Wide Field Instrument Industry Concept Study Underway: Ball Aerospace and Lockheed Martin ATC
- 6/9 –Project received APD direction to incorporate starshade compatibility into Phase A DRM – for SMD decision following SRR/MDR Spring 2017



Technology - Coronagraph

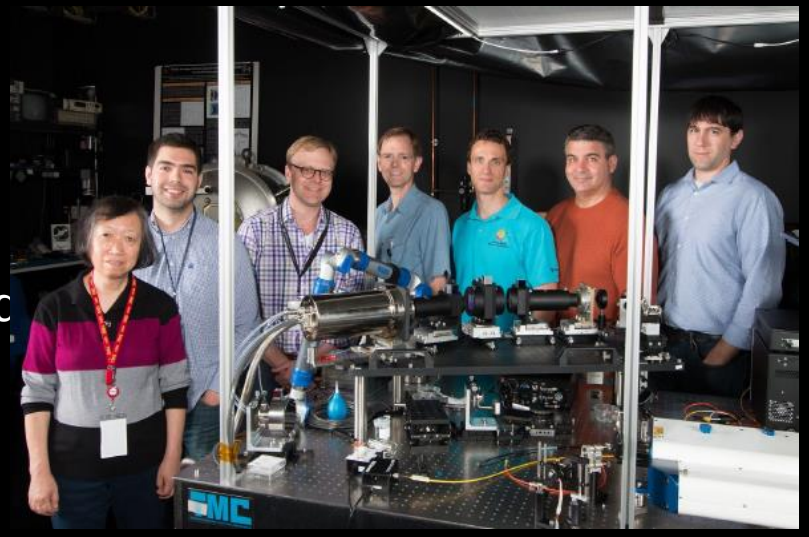
All prior WFIRST technology milestones met on schedule

PISCES Integral Field Spectrograph hardware delivered by GSFC to HCIT

- First demonstration of ultra-high contrast spectroscopy for characterization of exoplanets and image speckles
- Setup and initial testing this summer
- New PI Avi Mandell

Key upcoming milestones by 9/30/16:

- Read noise of EMCCD detector+readout
- First lab demo of PIAACMC coronagraph
- Demonstrate 10^{-8} raw contrast in 10% banc in a simulated dynamic environment



Exo-S Extended Probe Study completed

(Seager et al.)

- Options for follow-on missions with WFIRST, with operations at the Earth-Sun L2 point.
- Petal optimization for detection in blue band could improve Tech Demo and Extended Study IWA

Mission Option Characteristics							Performance Characteristics				
Option	Starshade Size	Mission Duration	Mission Class	Launch Option	Retarget Propulsion	Ball-Park Mission Cost	Search Mode IWA	Search Mode Bandpass	Telescope Separation	Exo-Earth Detections*	Exo-Earth Character-izations
Exo-S Tech Demo	20 m	1 yr.	D	Antares 3m fairing	Monoprop	$300M	100 mas	425-565 nm	20 Mm	≥1 candidate	0
Exo-S Extended Study	20 m	3 yr.	C	Falcon 9 5m fairing	Biprop	$450M	100 mas	425-565 nm	20 Mm	≥1	<1
Exo-S Case Study	34 m	3 yr.	C	Falcon-9 5m fairing	Biprop	$600M	70 mas	425-602 nm	50 Mm	≥2	≥1
Exo-S Enhanced	40 m	5 yr.	B	Falcon-9 5m fairing	SEP	$900M	50 mas	425-560 nm	82 Mm	≥4	≥2

Version	Parameters	Observing Bands		
		Blue	Green	Red
Case Study	Bandpass (nm)	425-602	600-850	706-1000
20m inner disk	IWA (mas)	70	100	118
28 7m petals	Separation (Mm)	50	35	30
Extended study	Bandpass (nm)	425-565	600-800	750-1000
10m inner disk	IWA (mas)	100	140	176
28 5m petals	Separation (Mm)	20.5	15	12

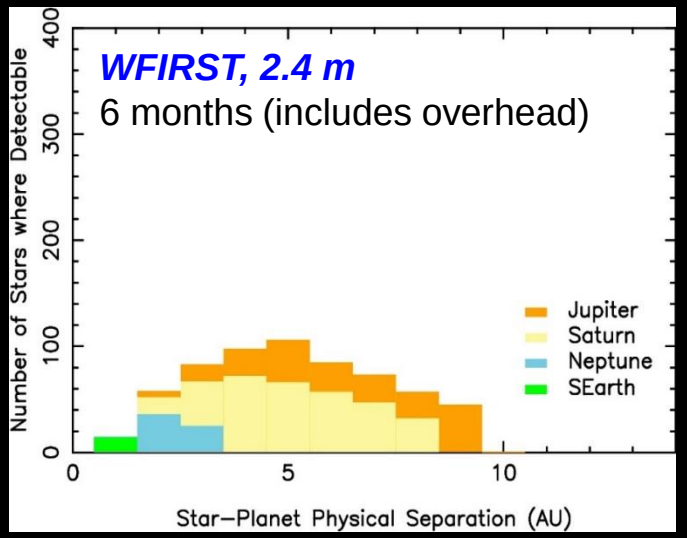
Exo-S ES compared to Exo-S CS

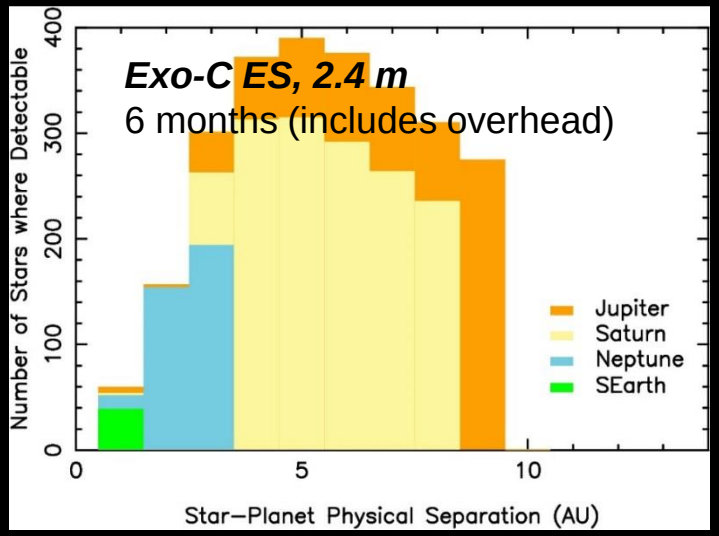
- **Discovery:** Stars that could be searched have the same quality images as before. Fewer targets with desirable IWA
- **Characterization by spectra:** only blue band is accessible for exoEarths
- **Background discrimination:** lack of colors at small IWA hurts for background contamination

Exo-C Extended Probe Study Completed

(Cahoy et al.)

- Exo-C ES report captures the science capability of a 2.4-m aperture space telescope designed specifically for exoplanet direct imaging.
- Highlights technology development needs beyond WFIRST:
  - 4k x 4k radiation-tolerant EMCCD detectors
  - 96 x 96 actuator deformable mirrors
  - Refinement and validation of contrast stability models to 10^{-11}
- Considered possible secondary payloads.
  - NIR coronagraph, Transit Spectrometer, NIRSpec “Lite”





NN-EXPLORE

Partnership for Exoplanet Discovery and Characterization

- Motivation
  - 2010 Decadal Survey calls for precise ground-based spectrometer for exoplanet discovery and characterization
  - Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)
  - Observations inform design/operation of future missions
- Scope:
  - Extreme precision radial velocity spectrometer (<0.5 m/s) for WIYN telescope contract is out
    - Penn State NEID proposal selected in March (see Chad Bender's talk tomorrow)
    - Instrument to be commissioned by July 2019
  - Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PennState

PI: S. Mahadevan

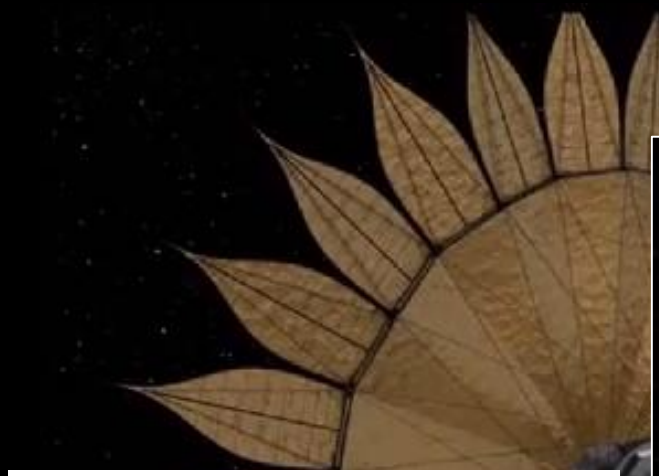
3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

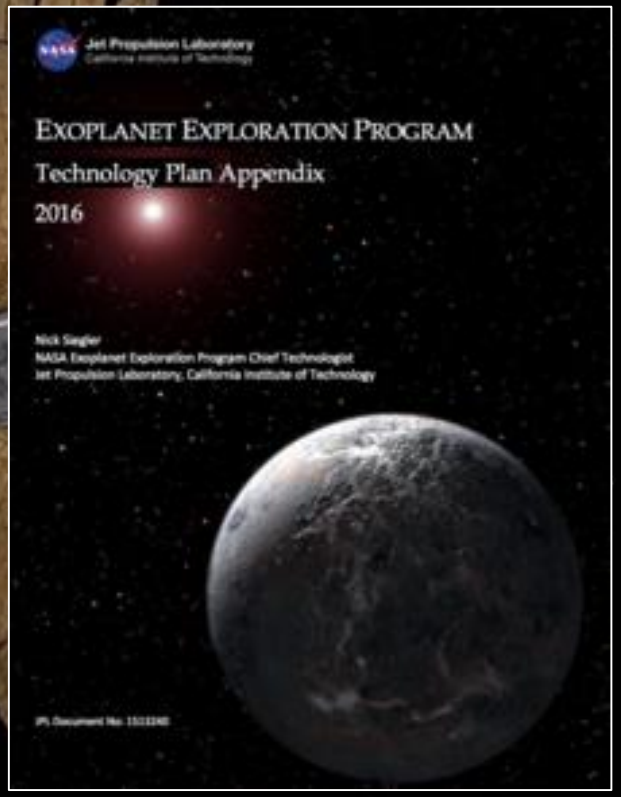
Strategic Astrophysics Technology - TDEM

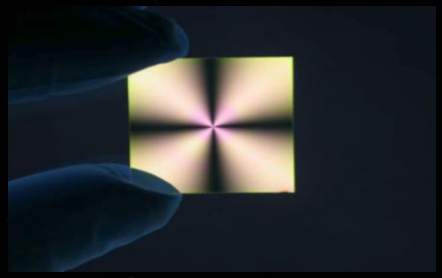
Reports for completed and active TDEMs: http://exep.jpl.nasa.gov/technology/
Reviewed and approved by ExoTAC, Alan Boss (chair)

- Active TDEMs
  - 2010
    - (Bierden) Environmental Testing of MEMs DMs
    - (Helmbrecht) Environmental Testing of MEMs DMs
  - 2012
    - (Kasdin) Optical and Mechanical Verification of External Occulter
  - 2013
    - (Bendek) Enhanced Direct Imaging with Astrometric Mass
    - (Cash) Development of Formation Flying Sensors
    - (Bolcar) Segmented Aperture Nulling Coronagraph
  - 2014
    - (Bolcar) Next Generation Visible Nulling
    - (Serabyn) Broadband Vector Vortex Coronagraph

ExEP Technology Gap Lists







Starshade Technology Gap List

Table A.4 Starshade Technology Gap List

ID	Title	Description	Current	Required
S-1	Control Edge-Scattered Sunlight	Limit edge-scattered sunlight with optical petal edges that also handle stowed bending strain.	Graphite edges meet all specs except sharpness, with edge radius ≥10 μm.	Optical petal edges manufactured of high flexural strength material with edge radius ≤ 1 μm and reflectivity ≤ 10%.
S-2	Contrast Performance Demonstration at Optical Model Validation	Experimentally validate the equations that predict the contrasts achievable with a starshade.	Experiments have validated optical diffraction models at Fresnel number of ~500 to contrasts of 3×10^{-10} at 632 nm.	Experimentally validate models of starlight suppression to ≤ 3×10^{-11} at Fresnel numbers ≤ 50 over 510-825 nm bandpass.
S-3	Lateral Formation Flying Sensing Accuracy	Demonstrate lateral formation flying sensing accuracy consistent with keeping telescope in starshade's dark shadow.	Centroid accuracy ≥ 1% is common. Simulations have shown that sensing and GN&C is tractable, though sensing demonstration of lateral control has not yet been performed.	Demonstrate sensing lateral errors ≤ 0.20m at scaled flight separations and estimated centroid positions ≤ 0.3% of optical resolution. Control algorithms demonstrated with lateral control errors ≤ 1m.
S-4	Flight-Like Petal Fabrication and Deployment	Demonstrate a high-fidelity, flight-like starshade petal and its unfurling mechanism.	Prototype petal that meets optical edge position tolerances has been demonstrated.	Demonstrate a fully integrated petal, including blankets, edges, and deployment control interfaces. Demonstrate a flight-like unfurling mechanism.
S-5	Inner Disk Deployment	Demonstrate that a starshade can be autonomously deployed to within the budgeted tolerances.	Demonstrated deployment tolerances with 12m heritage Astromesh antenna with four petals, no blankets, no outrigger struts, and no launch restraint.	Demonstrate deployment tolerances with flight-like, minimum half-scale inner disk, with simulated petals, blankets, and interfaces to launch restraint.

Coronagraph Technology Gap List

Table A.3 Coronagraph Technology Gap List.

ID	Title	Description	Current	Required
C-1	Specialized Coronagraph Optics	Masks, apodizers, or beam-shaping optics to provide starlight suppression and planet detection capability.	A linear mask design has yielded 3.2×10^{-10} mean raw contrast from 3–16 λ/D with 10% bandwidth using an unobscured pupil in a static lab demonstration.	Circularly symmetric masks achieving ≤ 1×10^{-10} contrast with IWA ≤ 3λ/D and ≥ 10% bandwidth on obscured or segmented pupils.
C-2*	Low-Order Wavefront Sensing & Control	Beam jitter and slowly varying large-scale (low-order) optical aberrations may obscure the detection of an exoplanet.	Tip/tilt errors have been sensed and corrected in a stable vacuum environment with a stability of 10^{-3} λ rms at sub-Hz frequencies.	Tip/tilt, focus, astigmatism, and coma sensed and corrected simultaneously to 10^{-4} λ (~10's of pm) rms to maintain raw contrasts of ≤ 1×10^{-10} in a simulated dynamic testing environment.
C-3*	Large-Format Ultra-Low Noise Visible Detectors	Low-noise visible detectors for faint exoplanet characterization with an Integral Field Spectrograph.	Read noise of < 1 e^-/pixel has been demonstrated with EMCCDs in a 1k × 1k format with standard read-out electronics	Read noise < 0.1e^-/pixel in a ≥ 4k × 4k format validated for a space radiation environment and flight-accepted electronics.
C-4*	Large-Format Deformable Mirrors	Maturation of deformable mirror technology toward flight readiness.	Electrostrictive 64x64 DMs have been demonstrated to meet ≤ 10^{-9} contrasts in a vacuum environment and 10% bandwidth.	≥ 64x64 DMs with flight-like electronics capable of wavefront correction to ≤ 10^{-10} contrasts. Full environmental testing validation.
C-5	Efficient Contrast Convergence	Rate at which wavefront control methods achieve 10^{-10} contrast.	Model and measurement uncertainties limit wavefront control convergence and require many tens to hundreds of iterations to get to 10^{-10} contrast from an arbitrary initial wavefront.	Wavefront control methods that enable convergence to 10^{-10} contrast ratios in fewer iterations (10-20).
C-6*	Post-Data Processing	Techniques are needed to characterize exoplanet spectra from residual speckle noise for typical targets.	Few 100x speckle suppression has been achieved by HST and by ground-based AO telescopes in the NIR and in contrast regimes of 10^{-5} to 10^{-6}, dominated by phase errors.	A 10-fold improvement over the raw contrast of ~10^{-9} in the visible where amplitude errors are expected to no longer be negligible with respect to phase errors.

*Topic being addressed by directed-technology development for the WFIRST/AFTA coronagraph. Consequently, coronagraph technologies that will be substantially advanced under the WFIRST/AFTA technology development are not eligible for TDEMs.

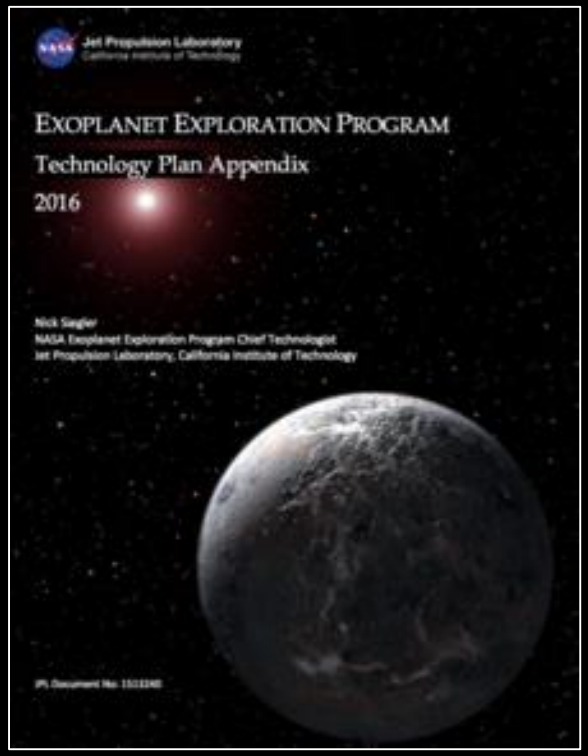
http://exep.jpl.nasa.gov/technology/

Strategic Astrophysics Technology - TDEM

Advancing Technology Readiness towards next Decadal Survey

- Sunday 9 am talk from Nick Siegler on how ExEP technology needs are identified and prioritized

Dr. Nick Siegler
Chief Technologist
Exoplanet Exploration



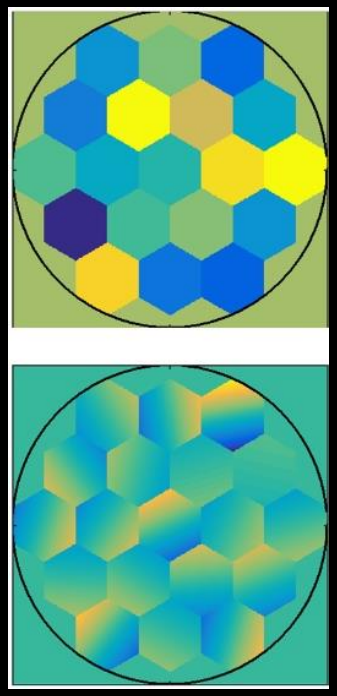
Progress towards 2010 Decadal Survey Priorities

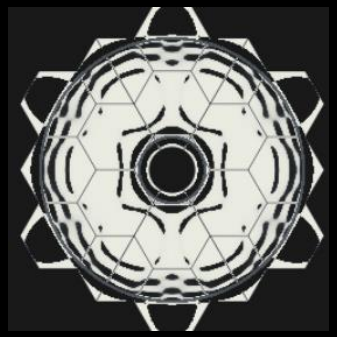
Program Updates

Preparations for 2020 Decadal Survey

High Contrast Imaging with Segmented Apertures

ExEP-sponsored workshop held at JPL, May 5-6 2016





SOC Chair Olivier Guyon

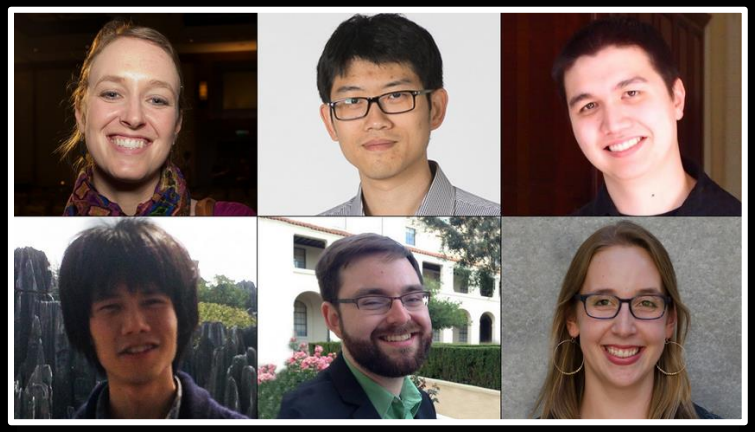
- Considered challenges posed by obscured & segmented apertures to coronagraphy and wavefront control
- Topics covered included
  - Segmented telescopes in development
  - Options for segmentation
  - Contrast dependence on segment misalignments (top left, Stahl & Stahl)
  - Coronagraph performance as a function of IWA and degree of segmentation (Zimmerman et al., lower left)
- 25 presentations available to review at https://exep.jpl.nasa.gov/hcisa/

Sagan Programs Update

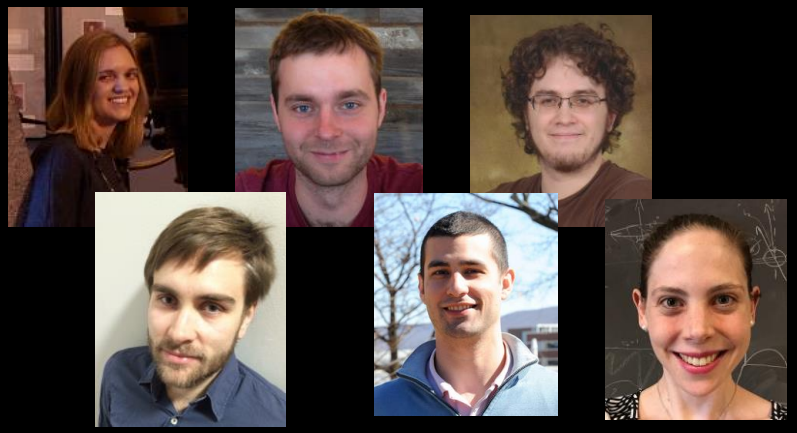
- Next Sagan Summer School
  July 18-22 2016 in Pasadena
  "Is there a planet in my data?"
- Six new 2016 Sagan Fellows selected

NExScI
NASA Exoplanet Science Institute

2016

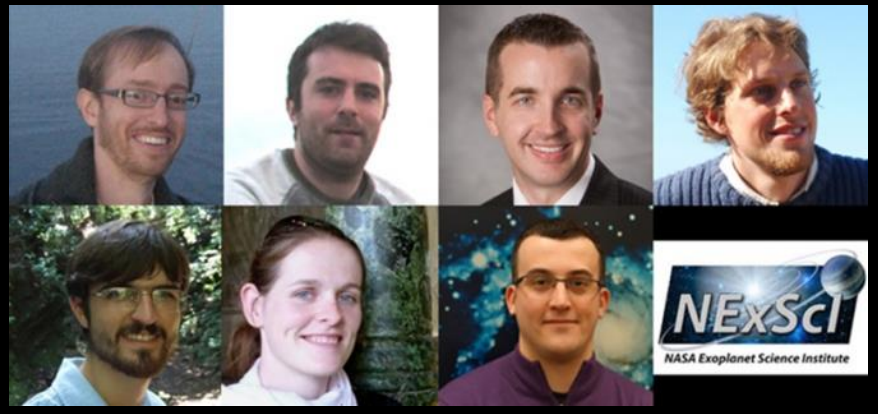


2015



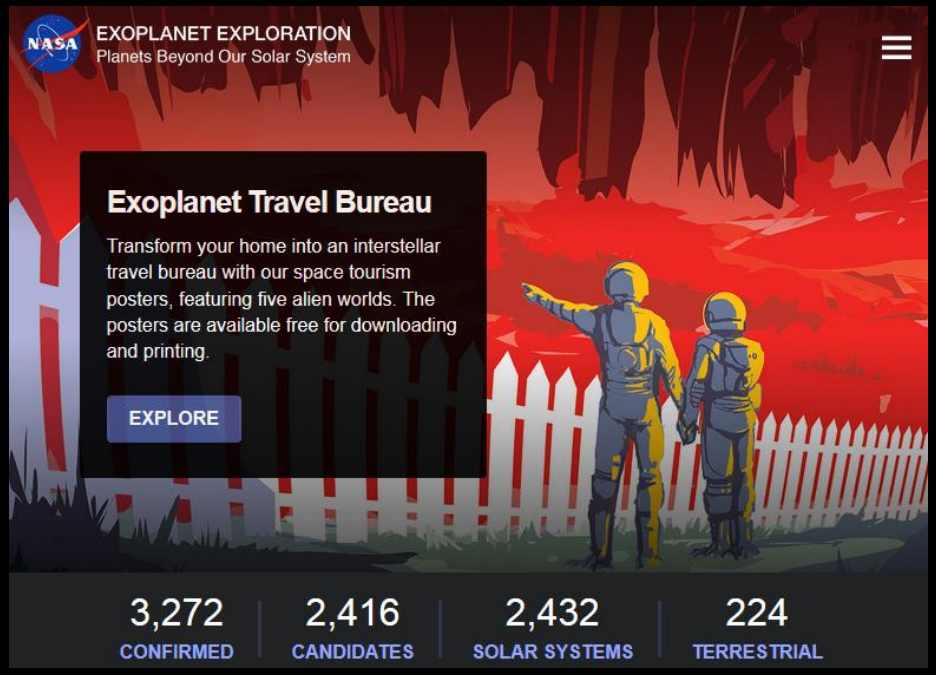
2013

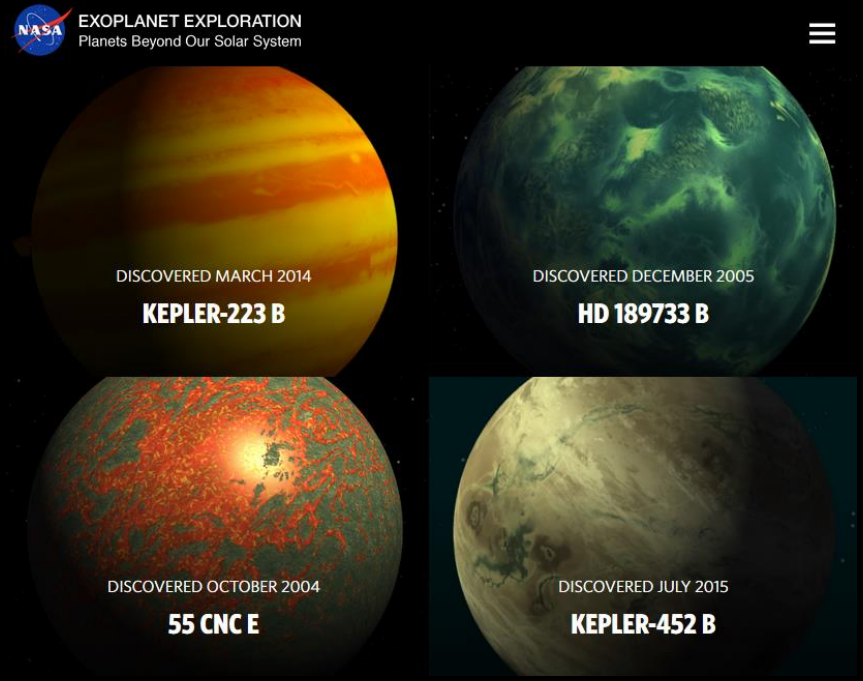
2014



New Public Website: NASA Exoplanet Exploration

exoplanets.jpl.nasa.gov





Replaces planetquest.jpl.nasa.gov
New content, compatibility with mobile devices,
some features of “eyes on exoplanets” incorporated

Progress towards 2010 Decadal Survey Priorities

Program Updates

Preparations for 2020 Decadal Survey

Large Binocular Telescope Interferometer

Measures exozodiacal dust in habitable zones

Phil Hinz, PI

THE UNIVERSITY OF ARIZONA

- Results of HOSTS survey to inform next decadal survey on direct exoplanet imaging: Survey deliveries planned for Sept 2016 and Sept 2017
- Demonstrated 12-15 zodi sensitivity for a solar twin at 10 pc at May 2015, <6 zodi single star sensitivity planned for April 2016 Science Operations Review
- HOSTS survey interrupted by glycol leak in secondary mirror, repairs complete January 2016
- No HOSTS science performed since last year – unable to complete (in-guide) the 32 star survey. Total of one HOSTS star thus far
- APD has a decision to make: Convene July 12 Continuation/Cancellation review at NASA HQs

LBTI instrument (green structure) mounted between the two LBT primary mirrors

Decadal Flagship Mission Studies

- Support science planning and yield estimates
  - Exoplanet Standard Definitions and Evaluation Team
  - See Rhonda Morgan's talk tomorrow
- Incorporate any mission concept's exoplanet technology requirements in Program Technology Gap list
  - Include telescope stability and detectors which apply to all architectures. See Nick Siegler's talk on Sunday
- High Contrast Imaging technology initiatives:
  - Segmented Coronagraph Design & Analysis: program-funded study to evaluate coronagraph designs suitable to segmented apertures. See Stuart Shaklan's talk tomorrow.
  - Experimental demonstration of 10^{-10} raw broadband contrast in HCIT. Goal of 2019 completion.

The Starshade Readiness Working Group (SSWG)

http://exep.jpl.nasa.gov/sswg/

- Require a risk reduction plan for technology validation of starshades to enable starshade flight science missions to be considered in 2020 Decadal Survey
- Will answer these questions and deliver recommendation:
  - How to go from TRL 5 to ~TRL6,7
  - Do we need a tech demo, and if so, what is it?
- Adopted the Exo-S probe “Starshade Rendezvous” as representative motivation of technology requirements
- Chairs: G. Blackwood (ExEP/JPL), S. Seager (MIT)
- Status:
  - Consensus reached on musts, wants; options defined, technical vetting underway.
  - Kickoff: January 2016, Report to APD: October 2016.

The Starshade Technology Project

- Purpose: achieve TRL5 by ~Decadal 2020
- Directed funding and reprogramming of competed funds
- March 23: APD Instructions to begin Planning Phase

Milestone	Description	Responsible Authority	Date
Design Review	Confirm updated reference mission is complete enough to begin tech development plan	Starshade Technology Project	May 2017
Technology Development Project Plan Review	Confirm technology development plan is complete and forms a good baseline to complete the planning of the implementation phase	Exoplanet Program Office	Jul 2017
Internal Planning Stage Review	Ensure Planning Stage Phase Plan is robust	JPL Director-for 7X	Aug 2017
Baseline TRL-5 Development Plan	Authorize start of Planning Stage Phase	SMD Astrophysics Division	Sep 2017

- Intent is broad institutional participation and funding
- Next step: Open workshop for work prioritization (Sept)

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. Chamberlin
Kepler / K2 Program Executive – J. Hayes
Kepler / K2 Program Scientist – Dr. M. Perez
NExScI, Keck, LBTI Prog. Exec. – Dr. M. Perez
NExScI, Keck, LBTI Prog. Sci. – Dr. H. Hasan
NExScI, Keck, LBTI Deputy Prog. Sci – Dr. K. Sheth
NN-EXPLORE Program Exec/Sci.- Dr. D. Hudgins

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 – K. Short
Program Chief Scientist – Dr. K. Stapelfeldt
Program Chief Technologist – Dr. N. Siegler

7301
Program Science Office
Chief Scientist – Dr. K. Stapelfeldt
Deputy Chief Scientist - Vacant
Dr. N. Gautier (326)
Dr. G. Bryden (326)

7303
Program Engineering Office
Program Chief Engineer – K. Warfield
Program Engineer - K. Warfield
Export Tech Lia. – Dr. A. Abramovici (383)
Mission Assurance Manager – J. Mehta

ExoPlanet TAC[1]
Dr. A. Boss
Carnegie Institution

7310
Program Business Office
Business Admin. Mgr – R. Lemus (731)
Administrator – O. Pananyan (731)
Project Acquisition Manager – W. Kert (268)
Staff Assistant – K. Miller (731)
Staff Assistant – J. Gregory (731)

Exoplanet
Probe Extended Study Office
K. Warfield (312)

Exoplanet Probe
STDT - Starshade[1]
Dr. S. Seager, MIT

Exoplanet Probe
STDT - Coronagraph[1]
Dr. K. Cahoy, MIT

7312
Business Operations
Resource Analyst – L. Scott (252)
Project Schedule Analyst – G. Luzwick (252)

Mission Managers
Kepler Mission Mgr – I. Heinrichsen (734)
WFIRST Mission Mgr – I. Heinrichsen (730)

790
NASA Exoplanet Science Institute (Caltech)
Exec. Director –
Dr. C. Beichman (790)
Deputy Director – Dr. R. Akeson
Manager – Dr. D. Imel

Kepler (ARC)
Project Manager (Phase E) – C. Sobeck
Project Scientist (Phase E) – Dr. S. Howell
Mission Scientist – Dr. N. Batalha
Guest Observer Office Dir. – Dr. T. Barclay

733
Program Technology (JPL)
Manager – Dr. N. Siegler, AD (383)

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

WFIRST Project Office (GSFC)
Project Manager – K. Grady
Deputy Project Manager – C. Peddie
Project Scientist – Dr. N. Gehrels

WFIRST Formulation Science Working Group
Project Scientist – Dr. N. Gehrels, GSFC
Dr. D. Spergel[1], Princeton
Dr. J. Kasdin[1], Princeton

Ground Observatories & Suborbital Activity (Caltech)
Manager – Dr. D. Imel
Keck Project Scientist –
Dr. R. Akeson

Starshade Technology Project (JPL)
Manager – TBD

735
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[1]Reports to NASA HQs APD

Legend:
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Interface - - - - -

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