The Future of NASA’s Exoplanet Exploration Program

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The Exoplanet Exploration Program: Exploring New Worlds

**Exploring** How the Universe Works
**Discovering** and Characterizing Exoplanets
**Searching** for Signs of Life in the Galaxy

Space Missions and Mission Studies

Kepler
AFTA
Probe-Scale:
External Occulter
(Starshade)
Coronagraph

Public Engagement

Supporting Research & Technology

Key Sustaining Research

Keck Single Aperture Imaging and RV
Large Binocular Telescope Interferometer

Technology Development

High Contrast Imaging
Deployable Star Shades

Archives, Tools & Professional Education

NASA Exoplanet Science Institute
NASA Astrophysics Missions

Recently Completed
Planck 2013
Herschel 2013
GALEX 2013
The Search for Life in the Universe Requires $\eta_{\text{Earth}}$

**Complete the census**
- **Kepler** (warm)
- **WFIRST** $\mu$-lensing (cool)

**Find nearby transiting planets**
- **TESS**

**Characterize super-earth/mini-Neptunes**
- **JWST**

**Imaging and Spectroscopy of planets**
- **WFIRST-AFTA coronagraph** (Jupiters, Neptunes, Super-Earths)
- **New Worlds Mission** (Earth 2.0)
Program Update – Kepler

• The flight system is behaving nominally in Point-Rest-State.
• The Call for White Papers resulted in 42 submitted papers covering exoplanets, asteroseismology, open cluster studies, NEOs, and more.
• An interim report on the potential science and operations of a 2-wheel Kepler mission (“K2”) was delivered to HQ in late Sept. Final report is due Nov. 20.
• A series of engineering demonstrations of 2-wheel performance on the spacecraft is under way.
• Path Forward
  – November 20 - Due date for final report from Kepler project on the science, operational strategy, and cost of a 2-wheel Kepler Mission. The report will be independently reviewed for both science and cost/technical feasibility.
  – NLT December 6 – HQ/ApD will respond to Kepler project with either approval to continue working on a K2 proposal for the Astrophysics Senior Review proposal or a decision to terminate Kepler Spacecraft operations if K2 concept is determined to be scientifically noncompetitive, technically infeasible, and/or cost prohibitive.
**Mission:** All-Sky, two-year photometric exoplanet mapping mission.

**Instruments:** Four WFOV CCD cameras with overlapping FOV of 23x90deg mounted in a common lens hood. Passively-cooled 600-1000nm 4096x4096 pixel FPA

**Science goal:** Will search for transiting planets around the brightest stars in the sky over a nominal 2-year mission.

- **Selection occurred April 5, 2013.**
- **Mission PI: George Ricker.**
- **Category 2, Class C mission managed within the GSFC Explorer Program.**
- **Tentative launch readiness date August 2017.**
- **High-Earth elliptical orbit (17 x 58.7 Earth radii).**
- **Development progressing on plan.**
  - **SRR tentatively planned for February/March 2014.**
- **No major milestones affected by the shutdown.**

**TESS**

Transiting Exoplanet Survey Satellite
Astrophysics Budget Strategy

- Use the scientific priorities of the 2010 Decadal Survey to guide strategy and inform choices.
- There is inadequate available budget to implement the 2010 Decadal Survey recommendations as written.
- In the absence of new missions, progress against decadal priorities is maintained through the core program: research and analysis (R&A), supporting and enabling technology development, operation of existing missions and their GO programs, the suborbital programs, and Explorer opportunities.
- A goal is to be prepared to start a new strategic Astrophysics mission to follow JWST as soon as funding becomes available, while continuing to advance Decadal Survey science during the interim.
Astrophysics Budget Strategy

• In order to be prepared for a new mission, a near term program of science definition teams, mission concept studies and technology development is being undertaken with the goal of informing a mid-decade decision on whether to begin formulation.

• Moderate missions (“probes”) are being studied, in addition to a large mission (WFIRST), to be prepared for a mid-decade decision.

• Mission concepts studied derive from the science objectives of the prioritized missions and recommendations in the 2010 Decadal Survey.
  - AFTA (WFIRST using existing 2.4 m telescopes)
  - WFIRST (2 design reference missions already studied, including WFIRST-probe)
  - X-ray Astrophysics Probe (moderate mission addressing IXO science)
  - Exoplanet Probes (moderate missions using internal or external occulters)
Preparing the next strategic mission

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<td>Spring 2013: Begin AFTA studies following Administrator’s decision</td>
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<td>Spring 2014: Interim SDT reports to NASA and CAA</td>
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Spring 2015: NRC study of all SDT reports resulting in a NRC letter report

ESA’s L2/L3 process

 Complete NRC Mid-Decade Review

Revise plans as necessary in response to Mid-Decade Review report

Initiate NRC Mid-Decade Review

Start Pre-formulation for new strategic mission
  - Directed/Focused technology development

Directed Technology investments for prime candidate

Technology Investments through SAT for prioritization

Technology Investments through SAT for 2020 Decadal Survey

Continuing advice from the Committee on Astronomy and Astrophysics on decadal survey implementation
We find that 22% of Sun-like stars harbor Earth-size planets orbiting in their habitable zones. The nearest such planet may be within 12 light-years. Petigura, Howard, Marcy 2013

Based on 3 years of data
104 habitable zone candidates
24 smaller than 2 Re.
Large Binocular Telescope Interferometer (LBTI)
University of Arizona

- **Instrument Status:**
  - All subsystems finalized and demonstrated on-sky.
  - Achieved open loop nulls on the sky.

- **Commissioning Status & Plans:**
  - Spring 2013 observing runs postponed due to failure of LBT adaptive secondary. Spare now ready.
  - Finalize commissioning during Fall 2013 (3 runs, 6 nights):
    - On-sky nulling with closed phase loop.
    - Optimized & automated data sequences.
    - First science demonstration data.
    - ORR planned for Jan 2014.

- **NExScI Archive:**
  - Level 0 data archive v 1.0: operational since Jul 2012.
  - Development plan:
    - L1 v 1.0: Dec 2013.
    - L2 v 1.0: Apr 2014.
    - L0 v 2.0: Jun 2014.

- **Science Team:** very active with data pipeline dev, definition of exozodi survey and target list, dev of observable modelling tools (leak \(\rightarrow\) zodis).

Science Capabilities: LBTI will enable characterization of exo-solar planetary systems
- Survey 50 nearby stars for exozodiacal dust, at levels of 3-6 times(1σ) the dust in our own planetary system.
Since Fall 2012, NASA has been studying potential uses of the 2.4 m telescope assets: (1) focused Astrophysics study (AFTA) and (2) an assessment of possible applications to other NASA objectives in science, technology, and human space flight.

The focused astrophysics study showed that use of these telescope assets satisfy all mission requirements for WFIRST. For approximately the same costs, the telescope assets would enable a WFIRST mission with significantly improved science capabilities relative to the design described in the Astrophysics Decadal Survey.

- AFTA’s 2.4 m aperture + Wide Field Imager meets (and exceeds) WFIRST requirements:
  - Higher spatial resolution enhances science capability.
  - Larger collecting area enables more science in fixed time.
- Use of the telescope assets would also enable the addition of an exoplanet imaging instrument to WFIRST that would enable imaging and characterization of planets around nearby stars up to a decade earlier than contemplated in the Decadal Survey; AFTA's 2.4 m aperture enables richer scientific return at much lower cost than a dedicated smaller coronagraphic telescope mission.

The Administrator directed the Science Mission Directorate to continue pre-formulation activities for a mission using the 2.4 m telescope assets to prepare for a later decision as to whether a WFIRST mission would be undertaken with these optics.

No decision on a future wide field infrared survey mission is expected until early 2016.

There was no decision to proceed with design studies for any other concepts at this time.
AFTA-WFIRST

- 2.4m aperture on-axis obscured telescope, 270K
- 28.5 degree inclination geosynchronous orbit, Atlas V 541 launch vehicle
- Two-channel widefield instrument with IFU channel 0.6 to 2.0 um for Dark Energy, NIR Surveys, and Exoplanet Microlensing
- FPA: 6x3 4kx4k HgCdTe detectors, 0.76 to 2.0 um
- Coronagraph instrument for Exoplanet Direct Imaging and Characterization
- Mission life 6 years with coronagraph
- Dedicated 18m Ka and S-band antenna in White Sands, NM. Ka-band downlink of 150 Mbps.

WFIRST final report May 23, 2013
http://wfirst.gsfc.nasa.gov/
AFTA Study: Near-Term Activities

• SDT is reconvened with new charter and additional members.
  – Co-Chairs are David Spergel (Princeton) and Neil Gehrels (GSFC).
• NASA requesting a NRC study in late 2013/early 2014 to assess AFTA design reference mission against Decadal Survey recommendations for WFIRST and New Worlds technology.
• APD down-selects to 2 coronagraph technologies for further development – decision by December 2013.
  – SDT delivered coronagraph science drivers analysis in early October 2013.
  – ExEP Program Office and AFTA Study Office coronagraph technology downselect recommendations due to APD December 2013.
• No decision on a mission will be made before early 2016.
  – Interim report by SDT and project due by April 2014.
  – Final report by SDT and project due by January 31, 2015.
  – CATE due February 27, 2015.
• NASA will request a study by the NRC in early CY 2016 of all SDT reports in context of Decadal Survey recommendations.
AFTA-WFIRST SDT Membership 2013-2015

Co-Chairs

David Spergel, Princeton
Neil Gehrels, GSFC

Members

Charles Baltay, Yale
David Bennett, Notre Dame
James Breckinridge, Caltech
Megan Donahue, Michigan State
Alan Dressler, Carnegie
Chris Hirata, Caltech
Scott Gaudi, Ohio State
Tom Greene, ARC
Olivier Guyon, Steward Observatory
Jason Kalirai, STScI
Jeremy Kasdin, Princeton
Bruce Macintosh, LLNL
Warren Moos, JHU
Saul Perlmutter, UC Berkeley
Marc Postman, STScI
Bernard Rauscher, GSFC
Jason Rhodes, JPL
David Weinberg, Ohio State
Yun Wang, Oklahoma

Ex Officio Members

Dominic Benford, NASA HQ (starting Sept 1, 2013)
Joan Centrella, NASA HQ (until Sept 1, 2013)
Yannick Mellier, IAP, France (ESA)
Wes Traub, JPL
Toru Yamada, Tohoku U., Japan (JAXA)

Consultants

Alina Kiessling, JPL
Matthew Penny, Ohio State U.
Dmitry Savransky, LLNL
Daniel Stern, JPL
Exoplanet detection by AFTA Microlensing

- Search field towards galactic bulge
- Sensitive to ~2800 bound planets
- Sensitive to hundreds of unbound, free-floater, (rogue) planets to ~Mars mass
- Helps complete the census begun by Kepler
Earth-mass planets from 1AU out
Really low-mass planets
AFTA Coronagraph Instrument will:

- Characterize the spectra of over a dozen radial velocity planets.
- Discover and characterize up to a dozen more ice and gas giants.
- Provide crucial information on the physics of planetary atmospheres and clues to planet formation.
- Respond to decadal survey to mature coronagraph technologies, leading to first images of a nearby Earth.
Sensitivity of AFTA Coronagraph for Imaging Exoplanets

- Survey of ~200 nearest stars within 30 pc
- Model assumes 4 planets per star with size distribution consistent with Kepler results, extrapolated to larger semimajor axis and lower mass
- Crosses: known RV planets
Technical Approach: Mask Technologies for High-Contrast Imaging

Downselect: 1/6/2014

<table>
<thead>
<tr>
<th>Primary approach</th>
<th>Back-up approach</th>
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<tr>
<td>Shaped Pupil Mask Pupil Masking (Vanderbei &amp; Kasdin, Princeton Univ.)</td>
<td>Vector Vortex Mask Image Plane (Serabyn, JPL)</td>
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<td>Phase Induced Amplitude Apodization (PAA) Pupil Ru Mapping (Gayon, Univ. Arizona)</td>
<td>Hybrid / Band Limited Lyot Mask Image Plane Amplitude &amp; Phase (Trauger, JPL)</td>
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<td>Visible Nuller Coronagraph: Phase-Occulting (Lyon, GSFC)</td>
<td>Visible Nuller Coronagraph: DaVinci (Shao, JPL)</td>
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TRL-6 @ PDR (10/2018)

TRL-5 @ start of Phase A (10/2016)
AFTA Coronagraph Technology Gaps

- **High Relative Gap and Urgency**
  - Architecture design (CG-1a)
  - Key component fabrication (CG-1b)
  - Contrast demonstrations (CG-6)
  - Low-order wavefront demonstrations (CG-2)

- **Medium Relative Gap and Urgency**
  - Flight readiness of DM and Fast Steering Mirror (CG-7)
  - Two-DM performance demonstration (CG-3)
  - End-to-end dynamic modeling (CG-5)

- **Less Urgent Gaps**
  - Post-processing of data (CG-4)
  - IFS pixel cross talk (CG-8)
  - Flight readiness of IFS detector (CG-9)
Exoplanet Probe Studies

• 2013 Astrophysics Division Implementation Plan calls for two probe-scale exoplanet missions,
  – Consideration by 2020 Decadal Survey
  – Guide technology investment for remainder of decade
  – Candidate for 2017 new start if AFTA cannot be started this decade

• Two Science and Technology Definition Teams (STDTs) selected
  – Exo-C: Probe coronagraph
  – Exo-S: Probe starshade (external occulter)

• Success criteria include: compelling science, viable technology, $1B life cycle cost ($FY15)

• STDT meetings (held jointly)
  – July 1-2, GSFC
  – September 11-12, MIT
  – November 14-15, JPL

• Mission concept reports and CATE due 1/31/15 and 2/28/15, respectively
# STDT Membership

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<tr>
<th>Last</th>
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<tr>
<td>* Stapelfeldt</td>
<td>Karl</td>
<td>NASA Goddard Space Flight Center</td>
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<tr>
<td>Belikov</td>
<td>Rus</td>
<td>NASA Ames Research Center</td>
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<tr>
<td>Bryden</td>
<td>Geoff</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>Cahoy</td>
<td>Kerri</td>
<td>Massachusetts Inst. of Technology</td>
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<tr>
<td>Chakrabarti</td>
<td>Supriya</td>
<td>Univ. of Massachusetts, Lowell</td>
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<tr>
<td>Marley</td>
<td>Mark</td>
<td>NASA Ames Research Center</td>
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<tr>
<td>McElwain</td>
<td>Michael</td>
<td>NASA Goddard Space Flight Center</td>
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<tr>
<td>Meadows</td>
<td>Vikki</td>
<td>Univ. of Washington</td>
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<tr>
<td>Serabyn</td>
<td>Gene</td>
<td>Jet Propulsion Laboratory</td>
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<tr>
<td>Trauger</td>
<td>John</td>
<td>Jet Propulsion Laboratory</td>
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<td>Sara</td>
<td>Massachusetts Inst. of Technology</td>
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<td>Cash</td>
<td>Webster</td>
<td>Univ. of Colorado</td>
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<td>Domagal-Goldman</td>
<td>Shawn</td>
<td>NASA Goddard Space Flight Center</td>
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<tr>
<td>Kasdin</td>
<td>N. Jeremy</td>
<td>Princeton Univ.</td>
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<td>Kuchner</td>
<td>Marc</td>
<td>NASA Goddard Space Flight Center</td>
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<td>Roberge</td>
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<td>NASA Goddard Space Flight Center</td>
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<td>Shaklan</td>
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<td>Sparks</td>
<td>William</td>
<td>Space Telescope Science Institute</td>
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<td>Thomson</td>
<td>Mark</td>
<td>Jet Propulsion Laboratory</td>
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<td>Turnbull</td>
<td>Margaret</td>
<td>Global Science Institute</td>
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<td>* Chair</td>
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Exoplanet Probe Study Office

- One Study Office, two coordinated design teams: fully staffed
  - Study Office Manager: Keith Warfield
  - Starshade Design Team Lead: Doug Lisman
  - Coronagraph Design Team Lead: Michael Brenner
  - Each has a full time team Leader and about 10 part time discipline experts

- Completed initial Team X studies of both configurations
  - Initial concepts for both probes designed and costed by JPL’s Team X
  - Team X design and cost models (and a Team X engineer) have been delivered to both design teams for quick mission-level trade studies

- Design trades are underway on both Design Teams
  - Error budgets, Mission-level trades
  - An initial telescope optical design established for the coronagraph STDT
    - Mechanical configuration work is underway on both teams

- An initial CATE meeting was held Sept. 3 with Aerospace Corp.
  - Aerospace presented and answered questions on the CATE process

- Preliminary prioritized technology needs delivered by both STDTs
Starshade Technology Gaps

- **High Relative Gap and Urgency**
  - System engineering, I&T Verification and Validation (SG-1)
  - Control of scattered light from petal edges (SG-5)

- **Medium Relative Gap and High Urgency**
  - Starshade deployment demonstration (SG-3)

- **Medium Relative Gap and Medium Urgency**
  - Validation of starshade models (SG-4)
  - Thermal and dynamic stability under flight conditions (SG-9)

- **Technologies with Lower Relative Gap**
  - Formation sensing for a dedicated telescope (SG-7)
  - Thruster technology for slew and science observations (SG-10)
  - Guidance, Navigation and Control for retargeting (SG-6)
  - Petal manufacturing (SG-2)
Starshade Technology

- Starshade technology TDEM led by PI Jeremy Kasdin: a first look test at deployment repeatability from a partially stowed position easily met 500 um deployment requirement
  - Four JPL-built starshade petals were integrated with a NGAS-Astro built inner disk structure and central hub at the Astro facility in Goleta, CA.
  - Integrated system successfully deployed multiple times with metrology of the deployed shape after each deployment.
Starshade Deployment
Exoplanet Exploration: A Decade Horizon
NASA-sponsored efforts

Program defines Success as three compelling, viable mission concept reports by 1/31/15 with CATE by 2/28/15
‘Eyes on Exoplanets’
Kepler Candidates—Available November 2013

http://exep.jpl.nasa.gov
Go to ‘planetquest’

- All 3,600 candidate systems shown in FOV
- Each confirmed planet can be visited
- Continuously updated as planets are confirmed
Very Near Future of Exoplanet Exploration Program

- **Probe Studies:** STDT meeting at JPL Nov 13-15, leading to interim report to HQs and CAA in March 2014
- **AFTA:** Decision on primary and backup architectures for coronagraph
- **January AAS:** evening sessions on AFTA, ExEP
- **Microlensing 14:** Santa Barbara, Jan 20-24
- **LBTI:** ORR January 2014
- **ROSES SAT TDEM 2013:** Proposals due March 21
- **June AAS:** Conference on exoplanet science with AFTA
Summary

- LBTI will measure exozodiacal dust levels in 50 nearby solar systems.
- AFTA will deliver exoplanet detections (microlensing) that complement the Kepler census, and exoplanet direct imaging of ice and gas giants.
- Mask technology down select underway.
- Technology priorities established, guide near term investments.
- Goal: 3 compelling, viable missions ready for potential FY17 new start.
- Look for AFTA and Probe Study presence at upcoming AAS meetings.
- We invite science community involvement in AFTA, Probe Studies, and in guiding the direction of the Exoplanet Exploration Program.
Exoplanet Missions

- JWST
- AFTA
- TESS
- New Worlds Telescope
- Kepler
- Spitzer
- Hubble
- Ground-based Observatories

2001 Decadal Survey

2010 Decadal Survey

Astronomy and Astrophysics in the New Millennium
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  – University of Arizona under a contract with the Jet Propulsion Laboratory
  – Princeton University, University of Arizona and Northrop Grumman Aerospace Systems under contracts with the National Aeronautics and Space Administration.

• The authors acknowledge contributions by Wes Traub, Peter Lawson, Nick Siegler, Michael Greene, Keith Warfield
BACKUP

Herschel cryogen depleted in April 2013

Launch in 2015
Launch in 2014
Launch in 2015
Launch in 2016
Launch in 2017
Launch in 2018
Launch in 2020

Planck mission completed in October 2013