Jet Propulsion Laboratory
California Institute of Technology

Exoplanet Exploration Program Update

Dr. Gary Blackwood, Program Manager
Dr. Karl Stapelfeldt, Program Chief Scientist
Jet Propulsion Laboratory
California Institute of Technology

January 02, 2017
Exoplanet Exploration Program Analysis Group Meeting (ExoPAG 15)
Grapevine, TX

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Artist concept of Kepler-16b

NASA Exoplanet Exploration Program

Astrophysics Division, NASA Science Mission Directorate

NASA's search for habitable planets and life beyond our solar system

Purpose described in 2014 NASA Science Plan

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

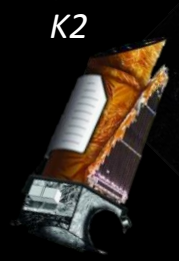
ExEP serves the science community and NASA by implementing NASA's space science vision for exoplanets

https://exoplanets.nasa.gov

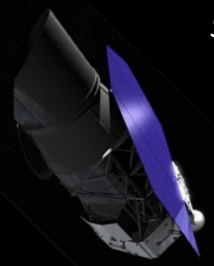
NASA Exoplanet Exploration Program

Space Missions and Mission Studies

Kepler, K2



WFIRST



Starshade

Decadal Studies

Coronagraph

Public Communications

Supporting Research & Technology

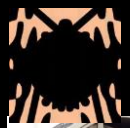
Key Sustaining Research

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

https://exoplanets.nasa.gov

New Leadership in ExEP Projects

Dr. Natalie Batalha,
Kepler Project Scientist
(ARC)

Dr. Jessie Dotson,
K2 Project Scientist
(ARC)

Dr. Margaret (Peg) Frerking
WFIRST Coronagraph Instrument Manager
(JPL)

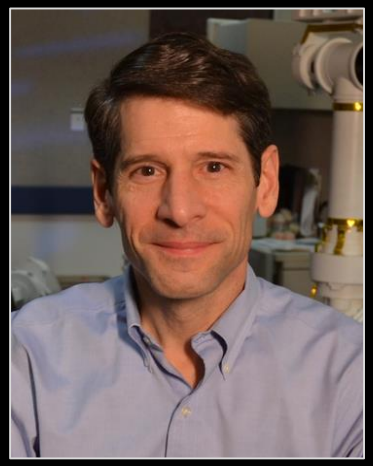
Dr. Feng Zhao
WFIRST Deputy Coronagraph Instrument Manager (JPL)

New Leadership in Exoplanet Program Office

Dr. Eric Mamajek,
Deputy Program Chief Scientist (JPL)

Tony Comberiate,
WFIRST Mission Manager (JPL)

Anya Biferno,
ExoComm Manager (JPL), acting



Dr. John Callas,
NN-EXPLORE Manager (JPL)

Dr. John Ziemer,
Starshade Technology Project Manager (JPL)

Bruce Nomoto,
Resource Analyst (JPL)

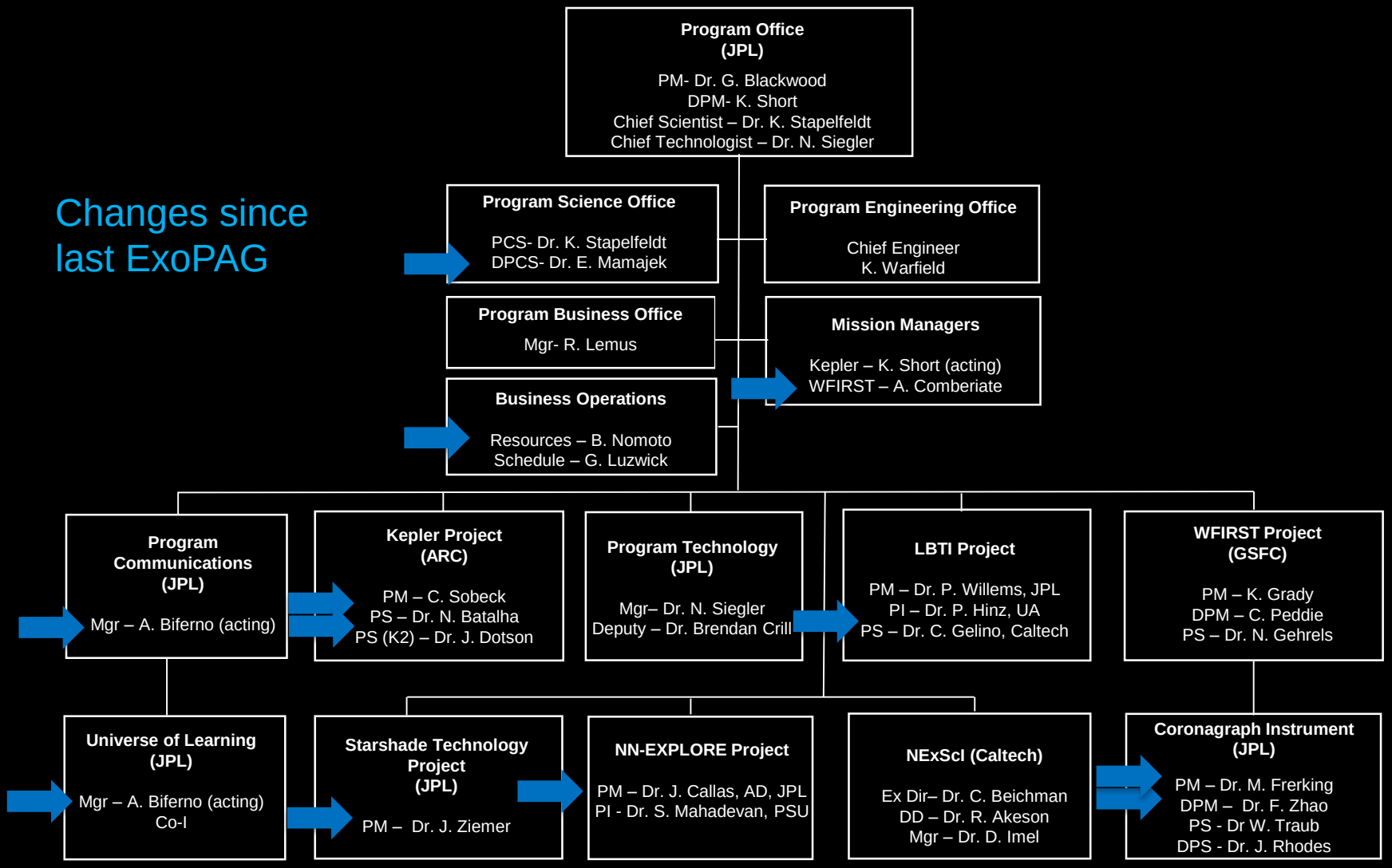
Dr. Chris Gelino,
LBTI Project Scientist (NExScI)

Dr. Brendan Crill,
Deputy Technology Development Manager (JPL)

NASA Exoplanet Exploration Program

Astrophysics Division, Science Mission Directorate

Changes since last ExoPAG



Astrophysics Division, NASA Science Mission Directorate

Resource Management
Omana Cawthon+
Clemencia Gallegos-Kelly+

Director
Paul Hertz

Deputy Director
Andrea Razzaghi

Lead Secretary: Kelly Johnson
Secretary: Kyle Nero
Program Support Specialist: Jackie Mackall

Cross Cutting

Technology Lead: Billy Lightsey*
Education POC: Hashima Hasan (Lead Comm Team)
Public Affairs Lead: Kartik Sheth
Information Manager: Lisa Wainio*
Strategic Planning: Rita Sambruna

Astrophysics Research

Program Manager:	Linda Sparke
Program Support:	Ingrid Farrell*
Astrophysics Data Analysis:	Doug Hudgins
Astrophysics Theory:	Keith MacGregor*, Theresa Brandt*
Exoplanet Research:	Martin Still*
APRA lead:	Michael Garcia*
Cosmic Ray, Fund Physics:	Thomas Hams*, Vernon Jones, Keith MacGregor*, Rita Sambruna
Gamma Ray/X-ray:	Dan Evans, Michael Garcia*, Stefan Immler*, Lou Kaluzienski, Rita Sambruna, Wilt Sanders
Optical/Ultraviolet:	Michael Garcia*, Hashima Hasan, Mario Perez*, Martin Still*
IR/Submillimeter/Radio:	Dominic Benford*, Doug Hudgins, Kartik Sheth, Eric Tollestrup*
Lab Astro:	Doug Hudgins
Theory & Comp Astro Net:	Keith MacGregor*
Roman Tech Fellows:	Billy Lightsey*
Data Archives:	Hashima Hasan
Astrophysics Sounding Rockets:	Wilt Sanders
Balloons Program:	Vernon Jones(PS), Mark Sistilli (PE)

Programs / Missions & Projects

	Program Scientist	*Program Executive*
Exoplanet Exploration (EXEP)		
Program	**Doug Hudgins**	**John Gagosian**
Keck	Hashima Hasan	Mario Perez*
Kepler/K2	Mario Perez*	Jeff Hayes
LBTI	Doug Hudgins	Mario Perez*
NN-EXPLORE	Doug Hudgins	John Gagosian
WFIRST	Dominic Benford*	John Gagosian
Cosmic Origins (COR)		
Program	**Mario Perez***	**Shahid Habib***
Herschel	Dominic Benford*	Jeff Hayes
Hubble	Michael Garcia*	Jeff Hayes
James Webb^	Hashima Hasan	Ray Taylor^
SOFIA	Hashima Hasan	Shahid Habib*
Spitzer	Kartik Sheth*	Jeff Hayes
Physics of the Cosmos (PCOS)		
Program	**Rita Sambruna**	**Shahid Habib***
Athena	Michael Garcia*	Jeanne Davis
Chandra	Stefan Immler*	Jeff Hayes
Euclid	Linda Sparke	Shahid Habib*
Fermi	Stefan Immler*	Jeff Hayes
Planck	Rita Sambruna	Jeff Hayes
ST-7/LPF	Rita Sambruna	Shahid Habib*
XMM-Newton	Stefan Immler*	Jeff Hayes
Astrophysics Explorers (APEX)		
Program	**Wilt Sanders**	**Jeanne Davis**
Hitomi	Lou Kaluzienski	Jeanne Davis
NICER	Rita Sambruna	Jeanne Davis
NuSTAR	Lou Kaluzienski	Jeff Hayes
Swift	Martin Still*	Jeff Hayes
TESS	Doug Hudgins	Mark Sistilli

\+ *Member of the Resources Management Division*
* *Detailee, IPA, or contractor*
^ *James Webb is part of the JWST Program Office.*

Dec, 06 2016

Kepler / K2

Progress towards 2010 Decadal Survey Priorities

Program Updates

What’s Coming Up

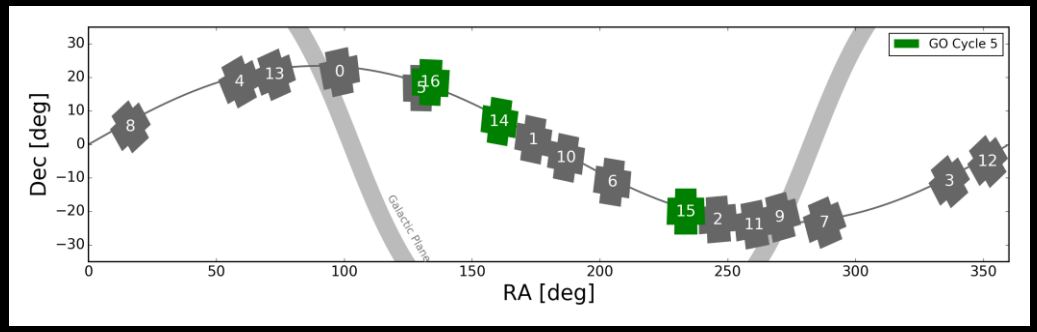
Kepler Close Out

Delivering Kepler's Legacy

- Kepler closeout and final data processing continues steadily within overall schedule margin
  - The final reprocessing of the Kepler Q0-Q17 short cadence light curves has been completed, and the files are online at MAST (8/8/16)
  - Held Successful Documentation Completeness Review (10/26/2016)
  - SOC 9.3 Final Occurrence Rate Products on track (April 2017)

Kepler K2

Extending the Power of Kepler to the Ecliptic



- Since last ExoPAG:
  - The C3, C4, and C5 short cadence data have been reprocessed and made available through MAST (Aug 16)
  - The Campaign 1 data has been reprocessed and is available on-line (Nov 16)
  - Processed Data released through Campaign 10 (Dec 16)
- Spacecraft remains fully operational, completed downlink of all Campaign 11 data via the DSN and is taking data on Campaign 12 field
- Changed the position of the field for Campaign 16 - Kepler will observe in the forward-facing direction. Significant fraction of pixels dedicated to supernova science.

https://exoplanets.nasa.gov/k2

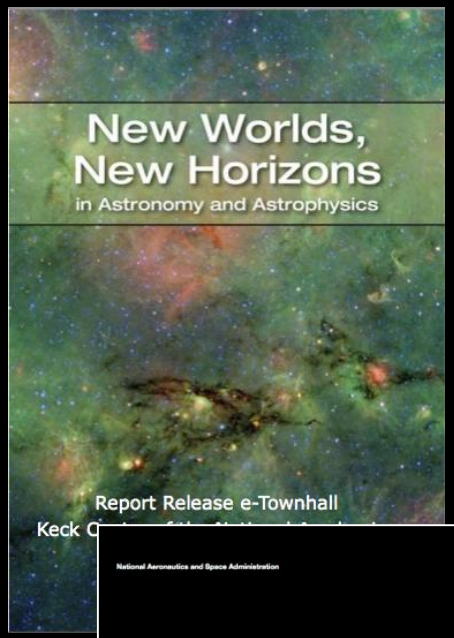
Kepler / K2

Progress towards 2010 Decadal Survey Priorities

Program Updates

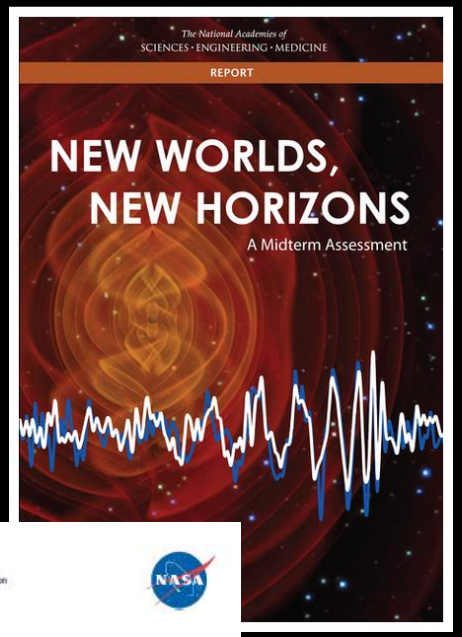
What’s Coming Up

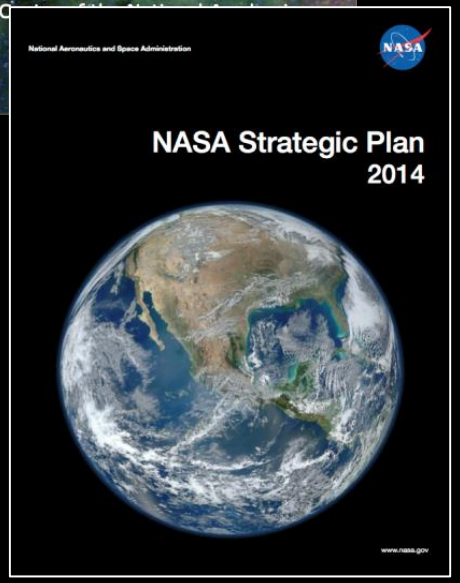
Astrophysics Division: Driving Documents

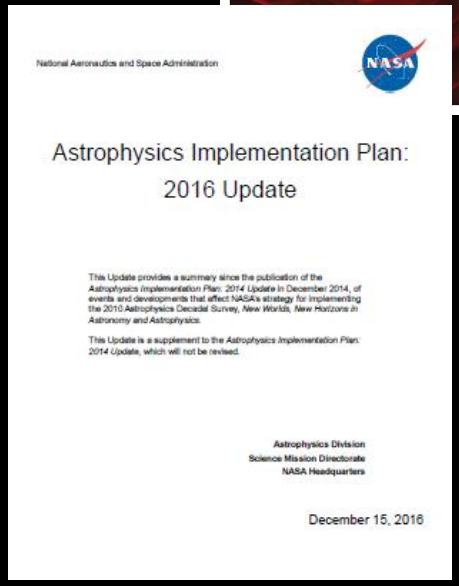


Results of NWNH:

- WFIRST is top large-scale recommended activity
- NWNH technology program is top medium-scale recommended activity







http://science.nasa.gov/astrophysics/documents

WFIRST

Dark Energy, Alien Worlds

- Completed Acquisition Strategy Meeting in August 2016
- Began Wide Field Instrument Industry 6-month Concept Study with Ball Aerospace and Lockheed Martin ATC
- WFIRST Project and the Formulation Science Working Group are finalizing trades and requirements in preparation for SRR/MDR in June 2017
- Preliminary starshade assessment indicates spacecraft accommodation is feasible
- Look ahead: Key Decision Point (KDP)-B in October 2017. Allen Bacskay (MSFC) appointed chair of Standing Review Board.

WFIRST Technology Milestones

- NIR Detector
  - Milestone 4: Completed. Full arrays demonstrate a yield of >20% (and meet derived requirements)
  - Milestone 5: Environmental tests of flight-like sensor chip assembly complete, report in preparation
- Coronagraph
  - Milestone 7: Completed. Spectrograph dark current <0.001 e/pix/s and read noise <1e/pix/frame
  - Milestone 8: Not met. PIAACMC $<10^{-8}$ raw contrast 10% broadband in static environment
  - Milestone 9: In progress. OMC $<10^{-8}$ raw contrast at 10% broadband in dynamic environment. Now resolving GSE limit (factor of ~2) to meet requirement

Large Binocular Telescope Interferometer

Measuring HZ Exozodiacal Dust, Informing Designs of Future Missions

Phil Hinz, PI

THE UNIVERSITY OF ARIZONA

- Termination Review held July 12 after year with only 1 HOSTS star measured. APD decision to continue HOSTS survey subject to binding NASA review at conclusion of 2017A semester: 32-star HOSTS survey delivery planned for September 2018
- 2016B Progress:
  - Three stars of HOSTS survey measured in November, and partial measurements on two more – bringing the HOSTS total to ~8 stars
  - HOSTS Survey prevented in (3 of 6) runs by problems with LBT adaptive secondary mirror, and in (1 of 6) runs by problems with LBTI slow pathlength corrector
- LBT planned to return to binocular operation for final 2016B run (January). ExEP will conduct Project Assessment Review in February 2017 to evaluate progress on HOSTS survey

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

- Motivation
  - 2010 Decadal Survey calls for precise ground-based radial-velocity spectrometer for exoplanet discovery and characterization
  - Follow-up & precursor science for current missions (K2, TESS, JWST, WFIRST)
- Scope:
  - Extreme precision radial velocity spectrometer (<0.5 m/s) for WIYN telescope development is underway
  - Instrument planned to be commissioned by Aug 2019
  - Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research. Please propose!
- Status
  - Held Instrument Detailed Design Review, and PDR for port adapter
  - Next steps: Disposition of Board recommendations, DDR for port adapter

NN-Explore Exoplanet Investigations with Doppler Spectroscopy

PennState

PI: S. Mahadevan

NOAO 3.5m WIYN Telescope
Kitt Peak National Observatory
Arizona

Strategic Astrophysics Technology - TDEM

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

- TDEMs pending final reports (by year of ROSES call in December):
  - 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
  - 2014
    - (Bolcar) Next Generation Visible Nulling
    - (Serabyn) Broadband Vector Vortex Coronagraph
  - 2015
    - (Breckinridge) Polarization in Coronagraphs

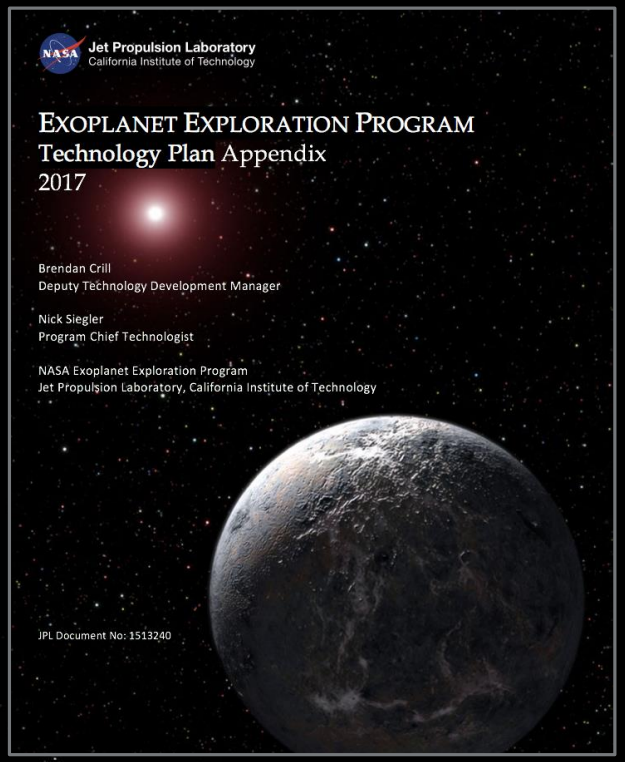
ExEP Technology Gap Lists

- **New Process for 2017 Technology Gap List**
  - ExEP solicited input from the community, in particular from large mission STDTs
  - ExoTAC reviewed selection and prioritization of Technology Gaps

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 and 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.

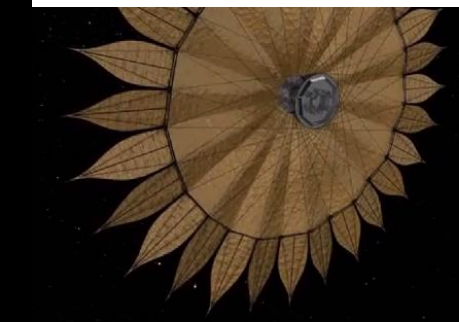


Coronagraph Technology Gap List

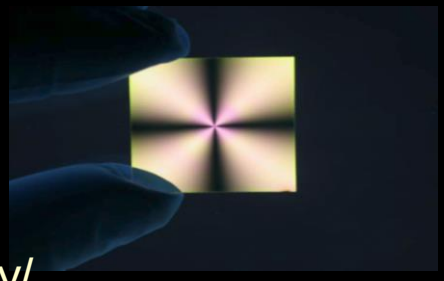
Table A.3 Coronagraph Technology Gap List.

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^{-3}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^{-9}, 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.



Appendix to be published
Mid-January 2017

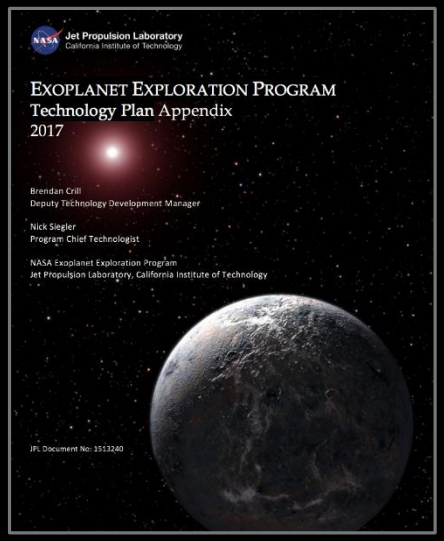


https://exoplanets.nasa.gov/technology/

Strategic Astrophysics Technology - TDEM

Advancing Technology Readiness towards next Decadal Survey

- Tuesday morning talks:
  - 9:00 am: Brendan Crill on how ExEP technology needs are identified and prioritized
  - 9:30 am Brendan Crill and Nick Siegler: discussion of ExEP's technology gap list



Appendix to be published Mid-January 2017

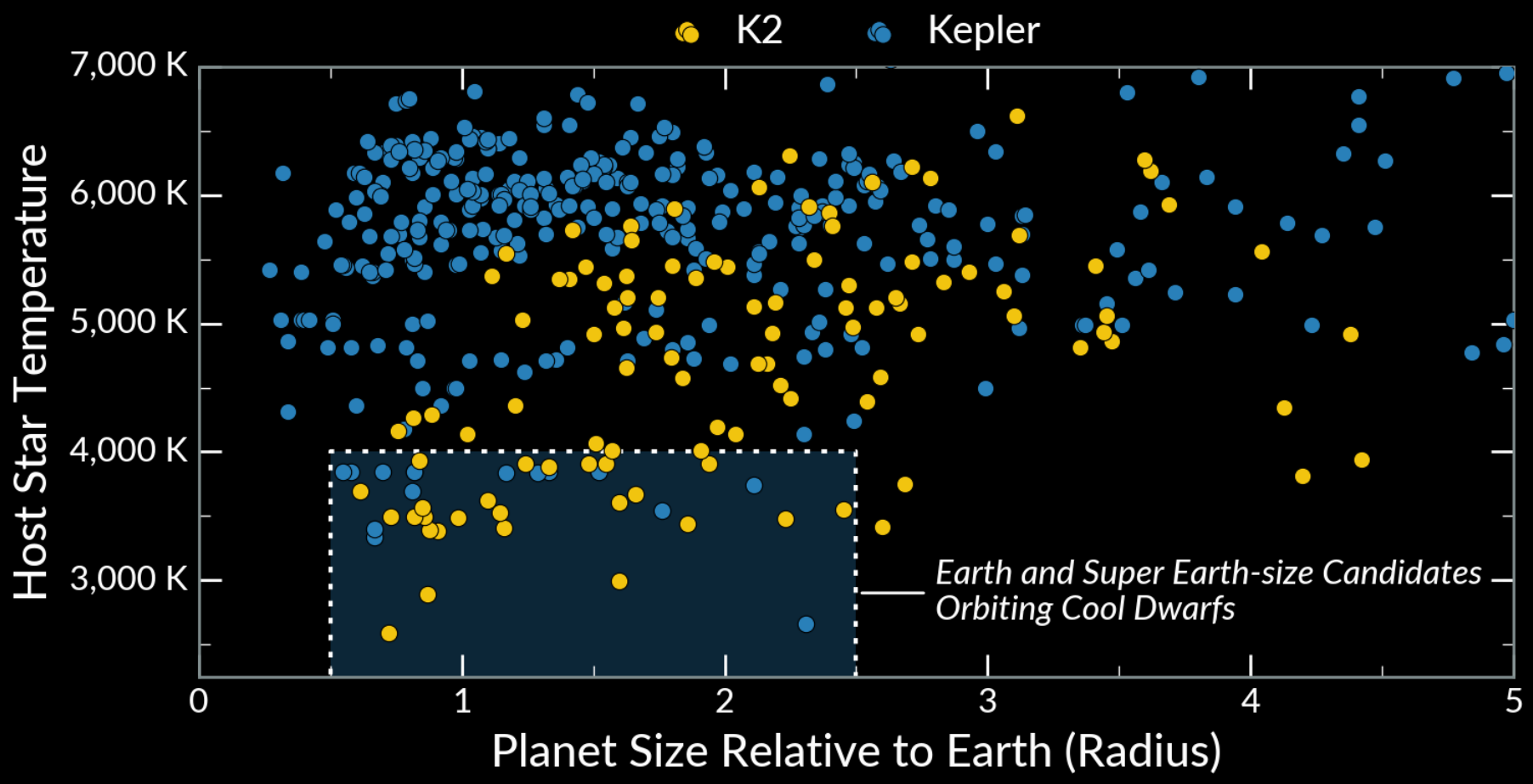
Kepler / K2

Progress towards 2010 Decadal Survey Priorities

Program Updates

What’s Coming Up

Planet Candidates for Atmospheric Characterization (Ks < 11)

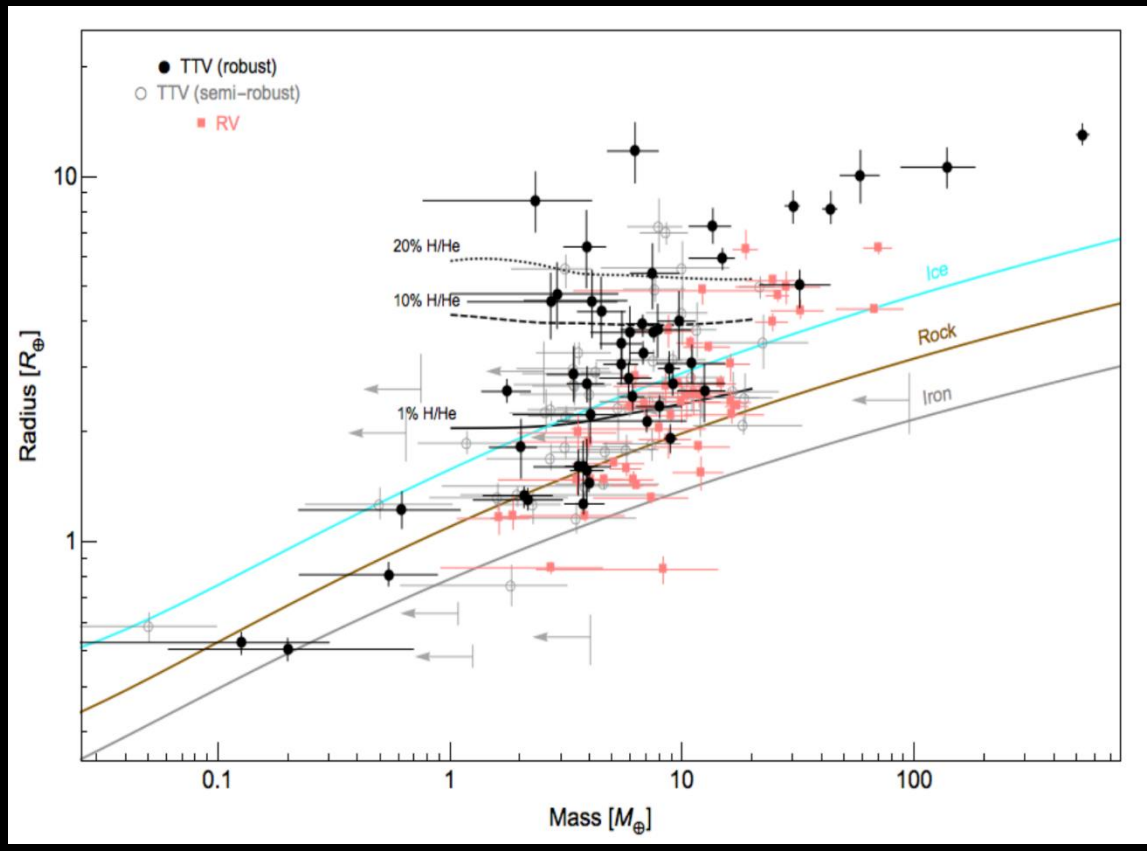


K2 / TESS splinter session: Wednesday 1/4 @7:30pm

Kepler Planet Masses and Eccentricities from Analysis of Latest TTV Catalog

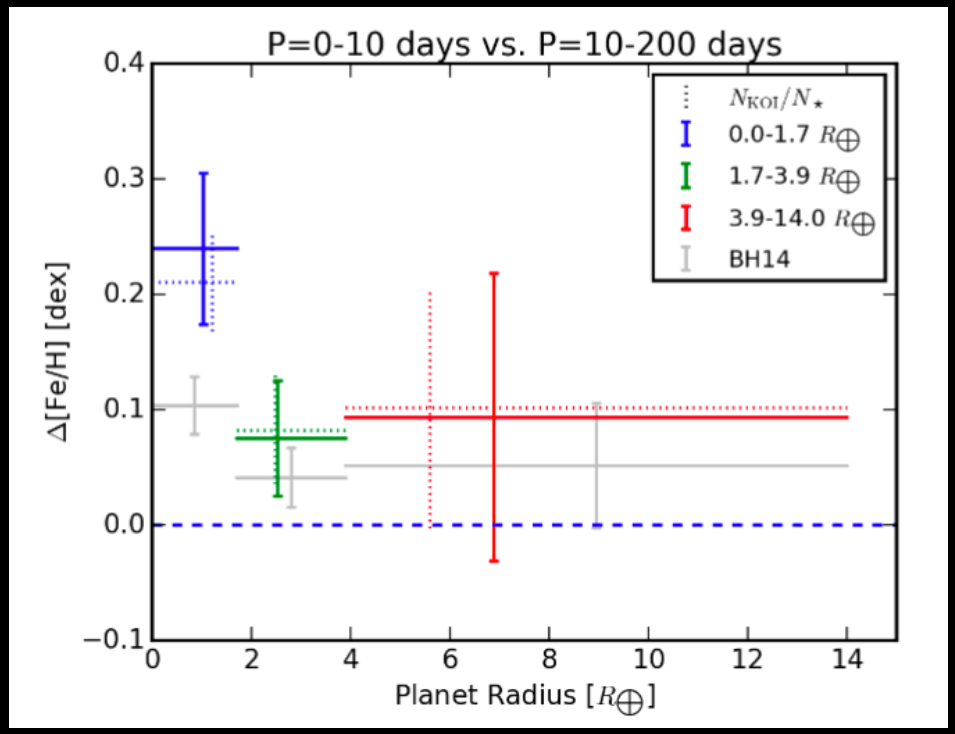
Hadden & Lithwick 2016 arXiv:1611.03516

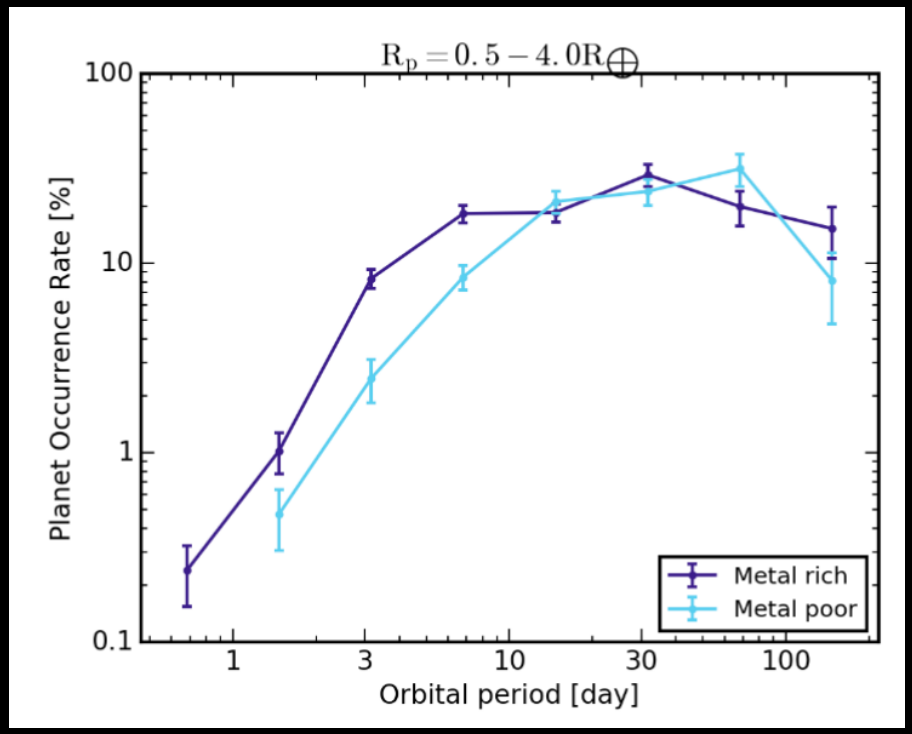
- 145 mass measurements, 80 of which are new
- 49 masses are robustly constrained, 12 of which are new
- 54 multi-planet systems; periods 10-100 days
- Low eccentricities in general but a few non-zero measured
- Presentation at AAS



A Super-Solar Metallicity for Stars with Rocky Exoplanets

Mulders et al. 2016 AJ 152, 187, arXiv:1609.05898

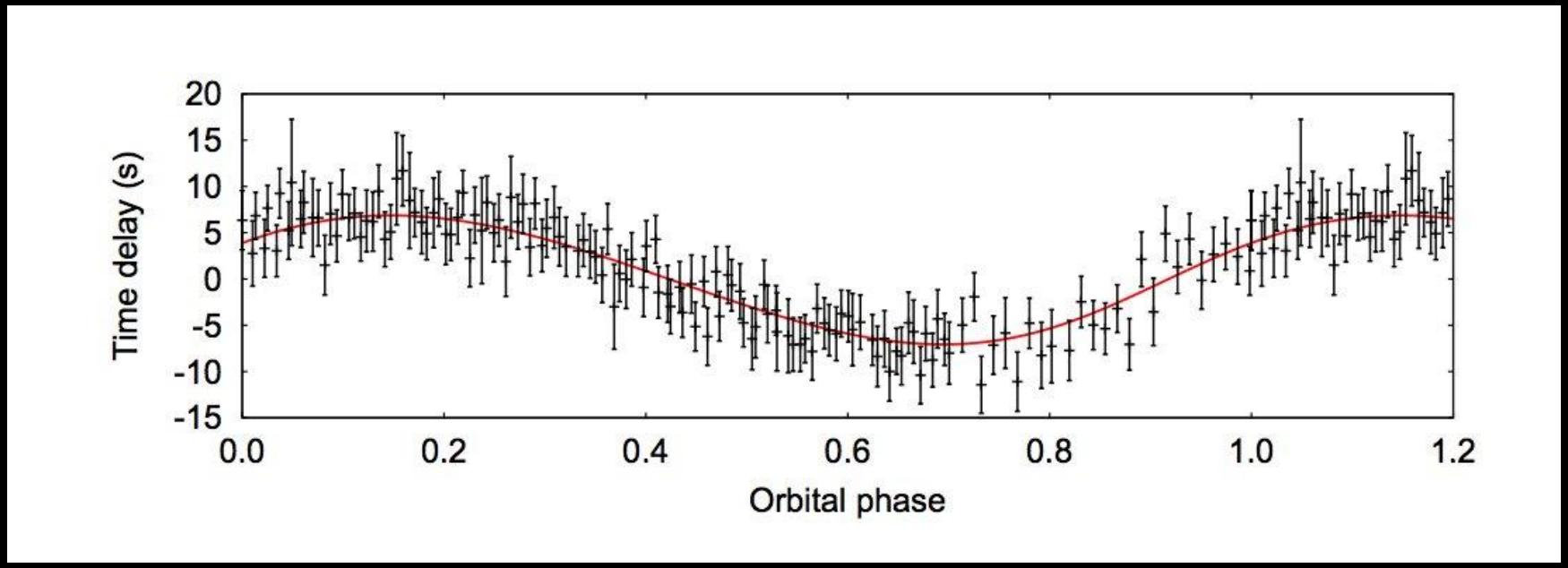




Host stars of short-period rocky planets (P < 10 days, R < 1.7 R_{Earth}) have enhanced metallicity (Δ[Fe/H]=0.25±0.07 dex) compared to mean planet host population (4σ difference in distributions via K-S test). **Metal-rich stars have 3x higher occurrence rate of small planets (<4 R_{Earth}) in short-period orbits (P < 10 days).**

Planet Orbiting A-type Main Sequence Star

Murphy & Bedding 2016 arXiv:1608.02945 (accepted)



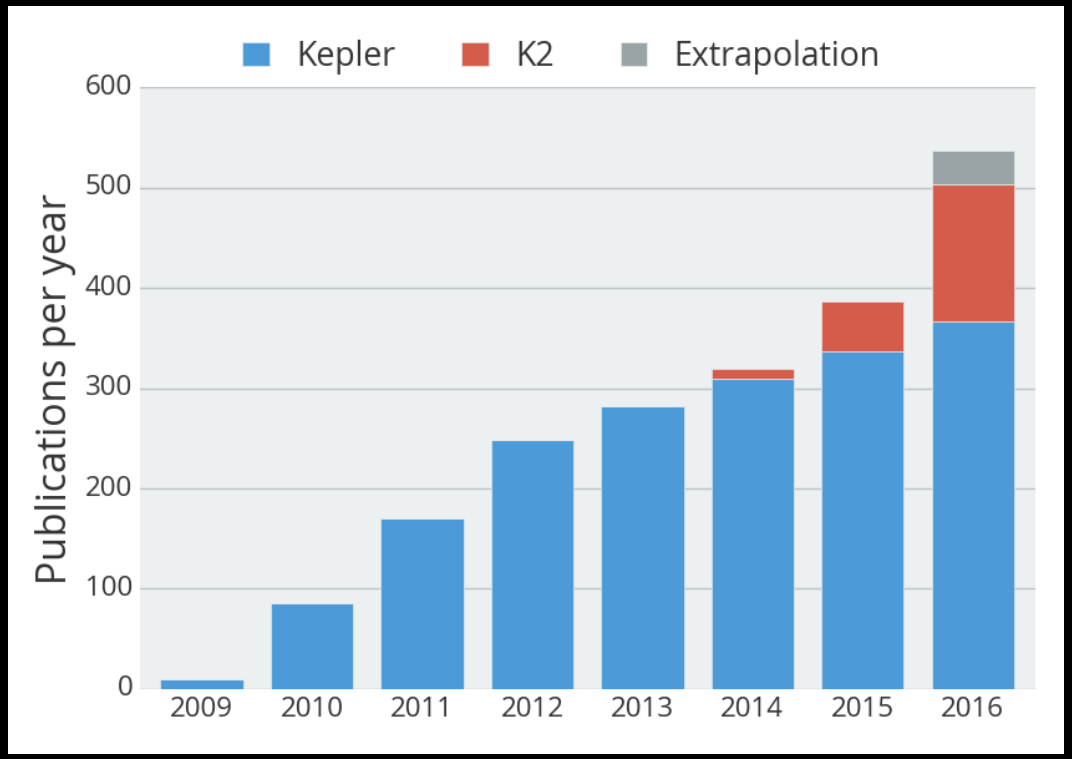
Planets orbiting A stars are hard to find via RV and transits due to rapid rotation, larger stellar radii, and pulsations.

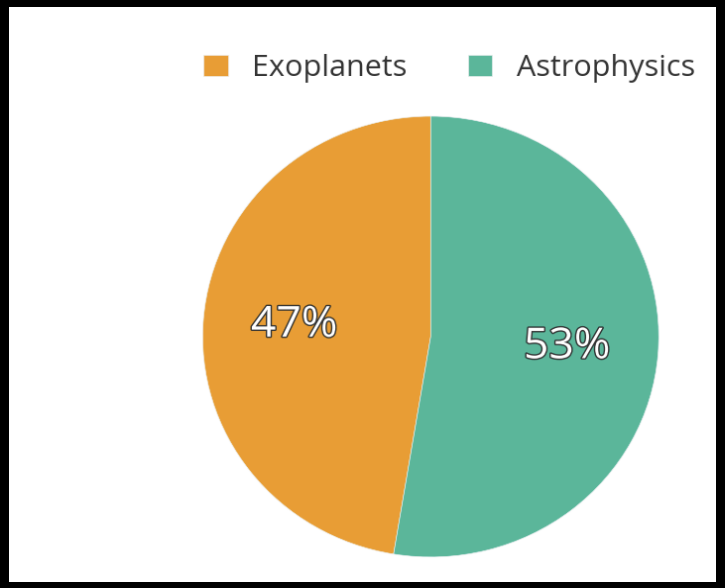
This planet identified via "light travel-time": tiny delays in pulsation arrival times. Only 14 second drift in 2.5yrs!

Kepler/ K2 Publication Statistics

2037 Publications, 1778 Peer-reviewed

as of 12/7/16



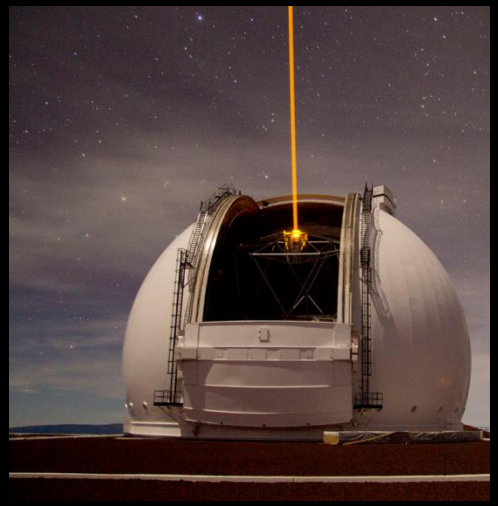


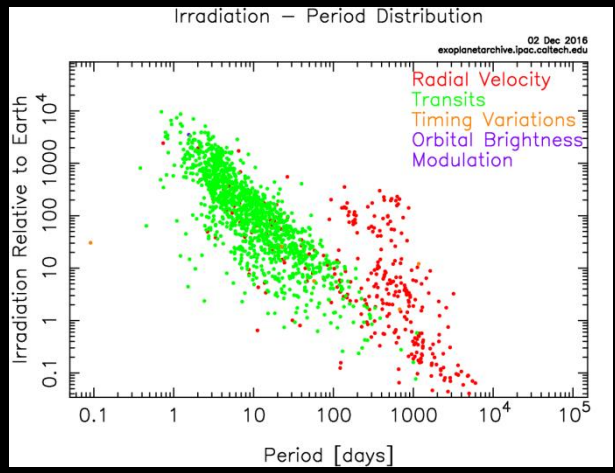
- The publication count for Kepler is 1838, that of K2 is 199
- Of the total, 965 relate to exoplanets (47%), 1071 to other areas of astrophysics (53%)

NASA Exoplanet Science Institute (NExScI) Update

- Sagan Summer School August 2016: "Is there a Planet in my Data?"
- Sagan Summer School August 2017: "Microlensing in the Era of WFIRST"

- NASA/Keck times (90 nights/yr) supports Exoplanets, Cosmic Origins, Physics of the Cosmos and Solar System science
- Exoplanet Archive tracks exoplanet population and Kepler pipeline products
- ExoFOP supports Kepler & K2 sources follow-up

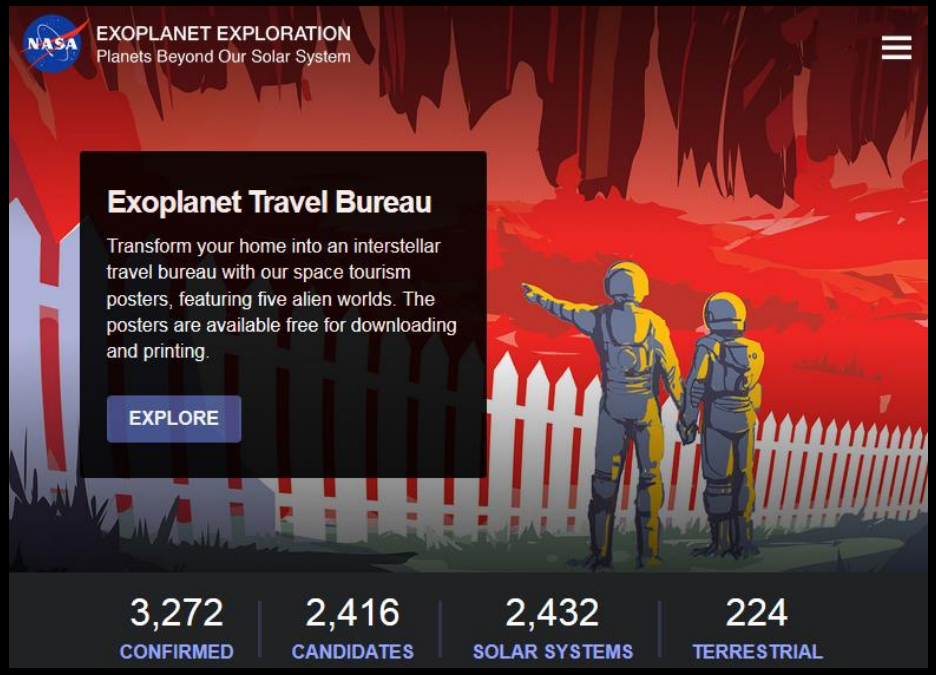




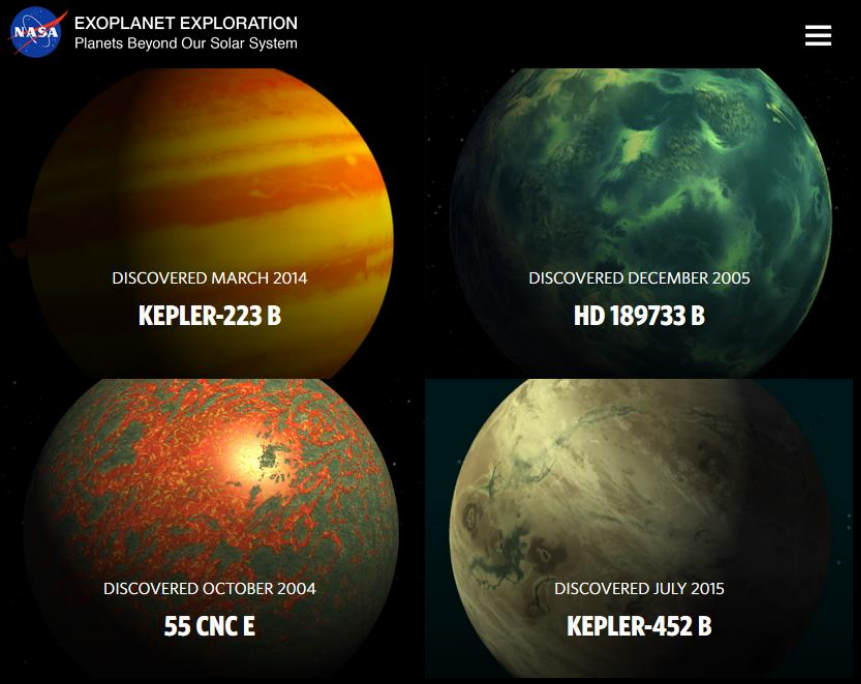
Exoplanet Communications

Data Visualization tools and new thematic exoplanet hub

exoplanets.nasa.gov



Replaces planetquest.jpl.nasa.gov
Exoplanet-thematic content featuring content across NASA.



3D, interactive planet renderings
Custom planet textures can be created for press releases.
(contact the Comm team in advance)

The Starshade Readiness Working Group (SSWG)

https://exoplanets.nasa.gov/exep/studies/sswg/

- Require a risk reduction plan for technology validation of starshades to enable starshade flight science missions to be considered in 2020 Decadal Survey
- Chartered to 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
- Broad participation; Chairs: G. Blackwood (ExEP/JPL), S. Seager (MIT)
- Final report delivered to APD Director 11/9/2016
- Among the findings:

1. A ground-only development strategy exists to enable a starshade science flight mission such as WFIRST Starshade Rendezvous
2. A prior flight technology demonstration is not required prior to KDP-C of WFIRST Rendezvous

Full briefing at link above, and on Friday Jan 6 starshade splinter session

The Starshade Technology Development Activity

Starshade to TRL 5 (S5)

- Purpose: achieve TRL5 to support future exoplanet missions with significant progress before 2020 Decadal Survey
- Currently developing a technology development plan as a recommendation to the Astrophysics Division in late 2017
- Held an all-day public Starshade Technology Workshop in Pasadena, CA on December 1, 2016
  - Broad institutional participation – over 80 local and remote participants from NASA, industry, and academia
  - Discussed the technology development needs and opportunities for future planning and prioritization
- Next steps: three follow-on workshops in late Feb-April for major technical themes and trades identified in the December workshop

Support for Decadal Large Mission Studies

- Charter signed for Exoplanet Standards and Definition Team
  - Completed ExoSIMS science planning and yield tool for large mission studies (Savransky, Morgan)
- Considered inputs from LUVOIR, HabEx, and OST in updated definition of Program Technology Gap list
- Made presentations to all four flagship study STDTs:
  - Keith Warfield (PCE) on lessons learned from prior decadal surveys
  - Gary Blackwood on Architecture trade methods
- High Contrast Imaging technology initiatives:
  - Segmented Coronagraph Design & Analysis: program-funded study to evaluate coronagraph designs suitable to segmented apertures. See Stuart Shaklan's recent online colloquium: https://exoplanets.nasa.gov/exep/technology/tech_colloquium/
  - Planning for Experimental demonstration of 10^{-10} raw broadband contrast in HCIT. Goal of 2019 completion.

Standard Definitions and Evaluation Team Update

- Charter Signed
  - Generalized to include FIRS for direct imaging
  - Does not include transit spectroscopy
  - https://exoplanets.nasa.gov/exep/resources/documents/
- EXOSIMS 1.0 is complete and validated (unit & integration tests)
- Inputs:
  - SAG13 Occurrence Rates nearing completion
    - Developing an EXOSIMS module for parameterized distribution
  - Chris Stark leading poll and discussion to select nominal HZ and earth-like radii
  - Avi Mandell leading draft definition of characterization metrics
  - Near Term open issues: albedo, eccentricity

Rhonda Morgan
Bruce Macintosh
Dmitry Savransky
Chris Stark
Avi Mandell
Ruslan Belikov
John Krist
Eric Nielson

STDT Liaisons:
Courtney Dressing
Karl Stapelfeldt
Klaus Pontoppidan

Kepler / K2

Progress towards 2010 Decadal Survey Priorities

Program Updates

What’s Coming Up

What's Coming Up

- AAS Sessions of Note:
  - New Methods for Teaching about Exoplanets
    Wed. Jan 4, 12:30-2:00 PM in Dallas 1
  - Science Opportunities with K2 & TESS,
    Wed. Jan 4, 7:30-9:00 PM in Texas C
  - WFIRST Status and Science Opportunities,
    Thurs Jan. 5, 7:30-9:00 PM Grapevine B
  - Starshade Development for Direct Imaging of Exoplanets,
    Friday Jan. 6, 2:00-3:30 PM in Appaloosa 1

- Upcoming conferences
  - 21st Microlensing Conference, Mar 1-3 Pasadena CA
  - 2017 Astrobiology Science Conference, Apr 24-28 Mesa AZ
  - Kepler/K2 SciCon IV, June 18-22 Mountain View CA
  - Astronomy in the 2020s: Synergies with WFIRST, June 26-30 Baltimore MD

Questions to Audience

- We will be organizing a workshop in the spring on telescope stability issues for high contrast imaging. We invite your suggestions on topics that should be covered.

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