NASA Exoplanet Exploration Program
Astrophysics Division, NASA Science Mission Directorate

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

Program 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
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 Manager (JPL)

Bruce Nomoto, Resource Analyst (JPL)

Dr. Chris Gelino, LBTI Project Scientist (NExScI)

Dr. Brendan Crill, Deputy Technology Development Manager (JPL)
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
WFIRST
Dark Energy, Alien Worlds, Infrared Astrophysics

• 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 Bacskey (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

• 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: 35-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

Phil Hinz, PI
• **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
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>
<thead>
<tr>
<th>ID</th>
<th>Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-1</td>
<td>Control-Scrambled Starshade</td>
<td>Optical edge must be smooth enough to handle AO correction.</td>
</tr>
<tr>
<td>5-2</td>
<td>Control Performance Demonstration</td>
<td>Experiments have validated performance of a 10-m starshade.</td>
</tr>
<tr>
<td>5-3</td>
<td>Lateral Formation</td>
<td>Demonstrates feasibility of industrial production.</td>
</tr>
<tr>
<td>5-4</td>
<td>Flight-Enable Pupil</td>
<td>Demonstrates flight-ability to a 10-m starshade.</td>
</tr>
<tr>
<td>5-5</td>
<td>Inner Disk Deployment</td>
<td>Demonstrates deployment tolerances with high optical performance.</td>
</tr>
</tbody>
</table>

**Coronagraph Technology Gap List**

<table>
<thead>
<tr>
<th>ID</th>
<th>Title</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-1</td>
<td>Selectable Coronagraph</td>
<td>Selectable coronagraph.</td>
</tr>
<tr>
<td>C-2</td>
<td>Low Order Wavefront Slicing</td>
<td>Attenuates the light of the star.</td>
</tr>
<tr>
<td>C-3</td>
<td>Large Format Transducer</td>
<td>Large format transducer.</td>
</tr>
<tr>
<td>C-4</td>
<td>Large Format Interferometer</td>
<td>Large format interferometer.</td>
</tr>
<tr>
<td>C-5</td>
<td>Efficient Contractors</td>
<td>Efficient contractors.</td>
</tr>
<tr>
<td>C-6</td>
<td>Fast-Data Processing</td>
<td>Fast-data processing.</td>
</tr>
</tbody>
</table>

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)

Earth and Super Earth-size Candidates Orbiting Cool Dwarfs

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

Replaced exoplanets.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 for consideration by the 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/
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/](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
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, February 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
Discussion topics: now and 11:30 Tuesday

• Radial velocity provides key precursor and follow-up data. NASA is funding NEID for WIYN. What should be the priorities for additional RV capabilities in support of NASA missions?

• ExEP 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.
Acknowledgements

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• Work was also carried out at NASA’s:
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  • Ames Research Center

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  • Princeton University
  • University of Arizona
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  • National Optical Astronomy Observatory (NOAO)
  • Massachusetts Institute of Technology
  • Pennsylvania State University