



NASA's Exoplanet Exploration Program:

*The Search for Planets, Habitability, and Life
in the Universe.*

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NASA Headquarters

Comm. on Astrobiology and Planetary Science
2 April 2015



NASA's Exoplanet Exploration Program

The overarching goals of NASA's Exoplanet Exploration Program (ExEP) as described in the 2014 NASA Science Plan are:

- To determine the abundance and distribution of extrasolar planets as a function of size, orbital radius, and other factors, in our galaxy.
- To understand the characteristics of exoplanets and exoplanetary systems including their formation, evolution, and composition.
- To find planets that may be habitable, and search for the fingerprints of extant life on those planets.





NASA's Exoplanet Exploration Program

Observational approach to achieving ExEP goals

- **Discovering Planets:** How abundant are exoplanets?
 - *Radial Velocity*
 - *Transit Photometry*
 - *Gravitational microlensing*
- **Characterizing Planets:** What are exoplanets like?
 - *Radial Velocity*
 - *Transit Spectroscopy*
 - *Direct Imaging and spectroscopy*
- **“Earth 2.0”:** Are the planets habitable and do they exhibit signs of life?
 - *Transit Spectroscopy (better than 1 part per million)*
 - *Direct Imaging*
 - High Contrast: *better than 1×10^{-10}*
 - Small Inner Working Angle: *less than 100 mas*
 - Spectroscopic resolution: *$R \sim 100$ in visible, near infrared*

Exoplanet Exploration

Mission Trajectory for advancing Exoplanet Science goals

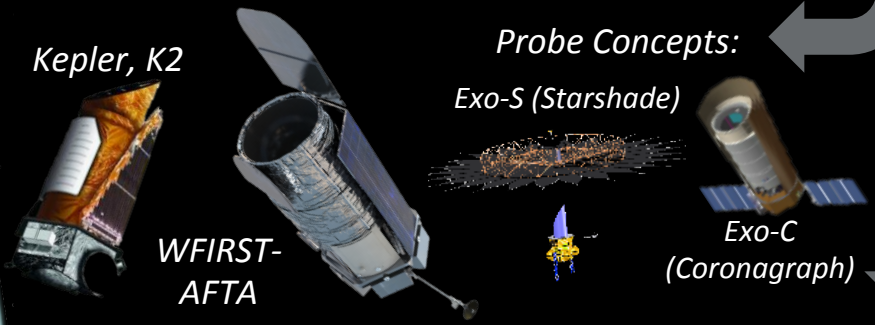




The Exoplanet Exploration Program

Exoplanet Exploration

Current and Future Flight Missions



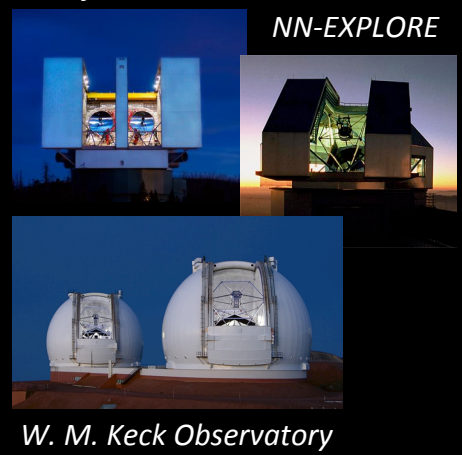
Public Engagement



Supporting Research & Technology

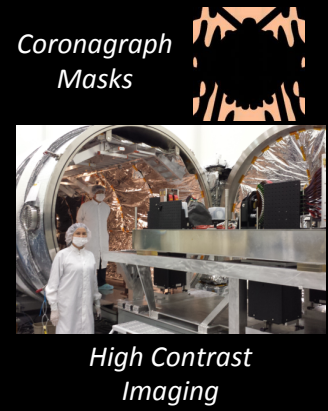
Mission Enabling Research

Large Binocular Telescope
Interferometer



Technology Development

Coronagraph
Masks



Deployable
Star Shades



NASA Exoplanet Science Institute



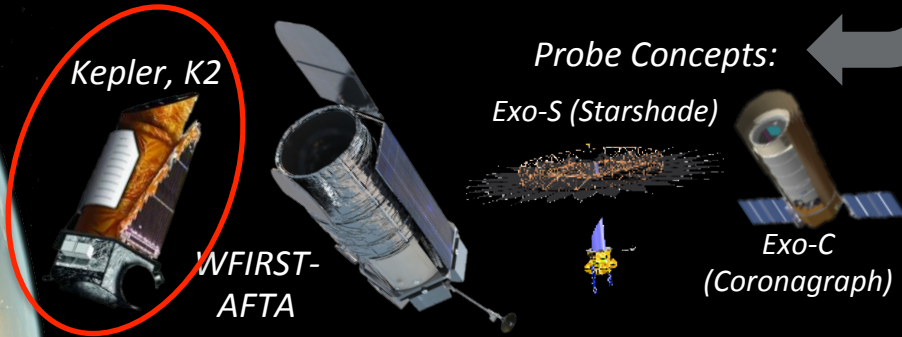
Archives, Tools,
& Professional Education



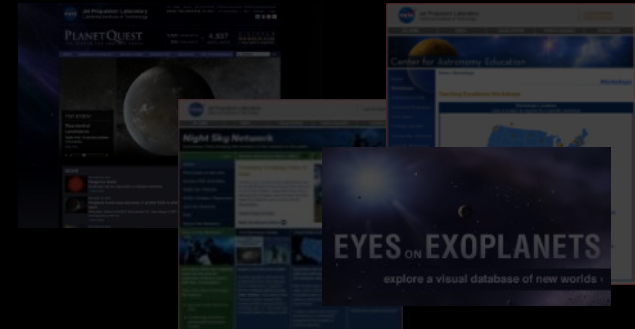
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Current and Future Flight Missions



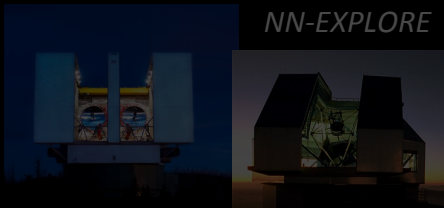
Public Engagement



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W. M. Keck Observatory

Technology Development

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High Contrast
Imaging



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NASA Exoplanet Science Institute



Archives, Tools,
& Professional Education

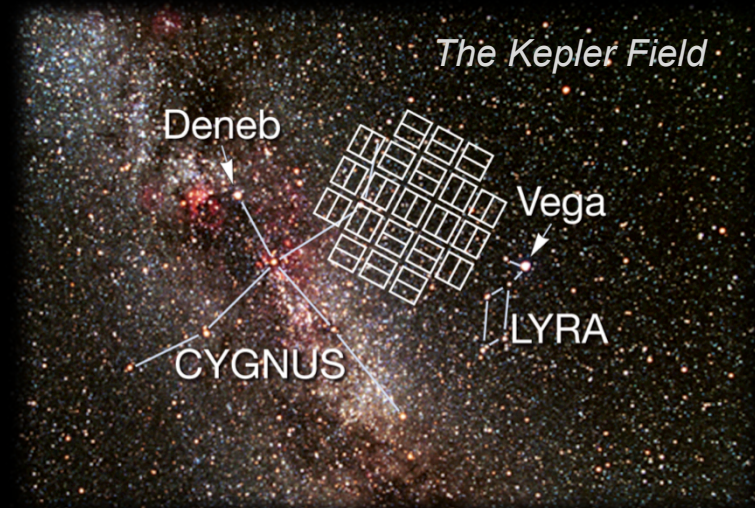


The Kepler Mission



Kepler was selected as the 10th *Discovery* Mission and represents NASA's first space mission dedicated to the search for exoplanets.

- Payload: 0.95-meter diameter telescope capable of continuously monitoring more than 150,000 stars with a photometric precision sufficient to measure the transits of exoplanets as small as $\sim 1 R_{\oplus}$
- PI: W. Borucki, NASA Ames Research Center
- Launch Date: March 6, 2009
- Scientific objectives:
 - *conduct census of exoplanet systems*
 - *explore the structure and diversity of extrasolar planetary systems*
 - *determine the frequency of habitable, Earth-sized planets in our galaxy*



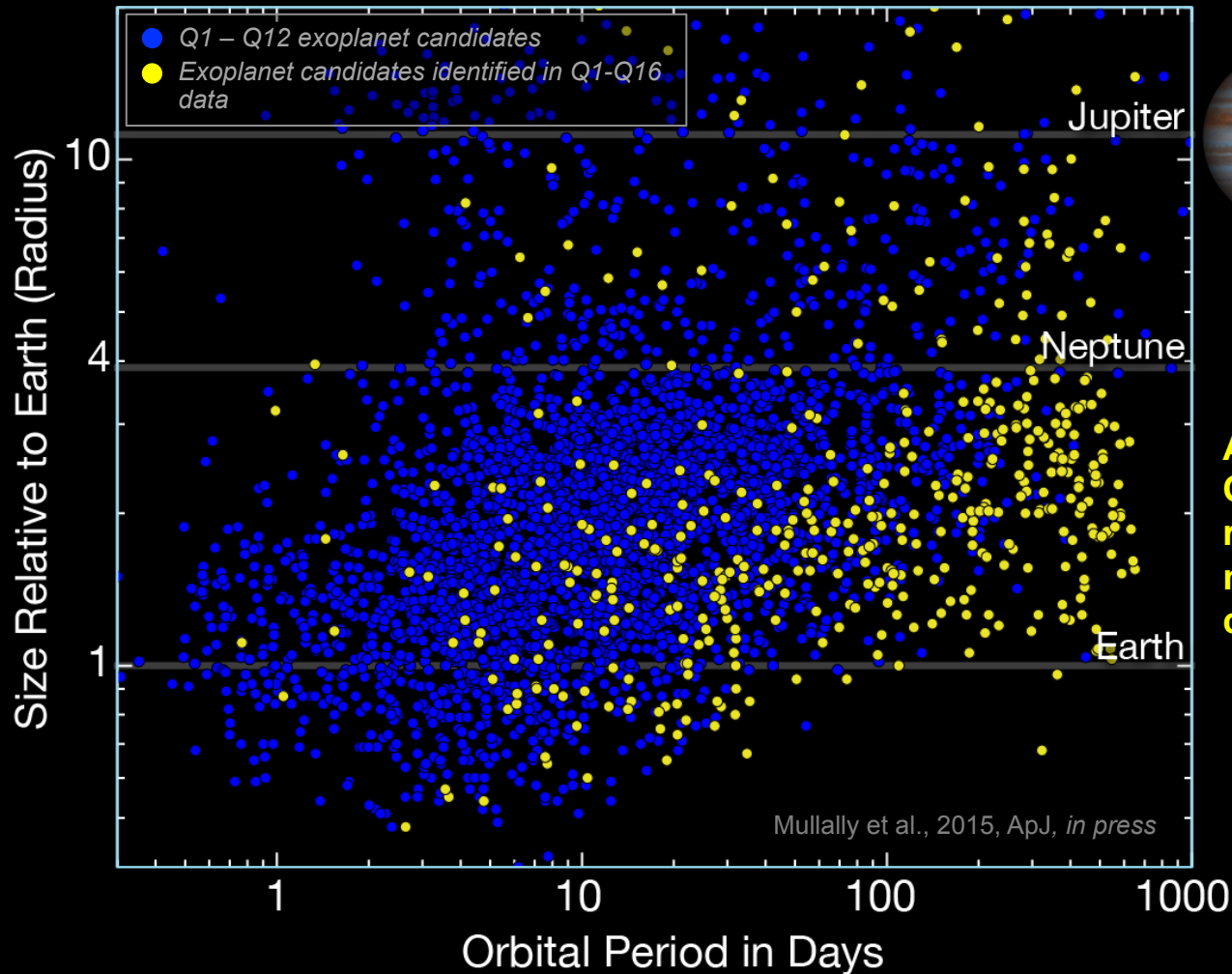
- For more than 4 years, from 2009-13, Kepler monitored a 100 sq. deg. field straddling the constellations of Cygnus and Lyra.



New Kepler Exoplanet Candidates



Total Exoplanet Candidates = 4175
Confirmed Exoplanets = 1019

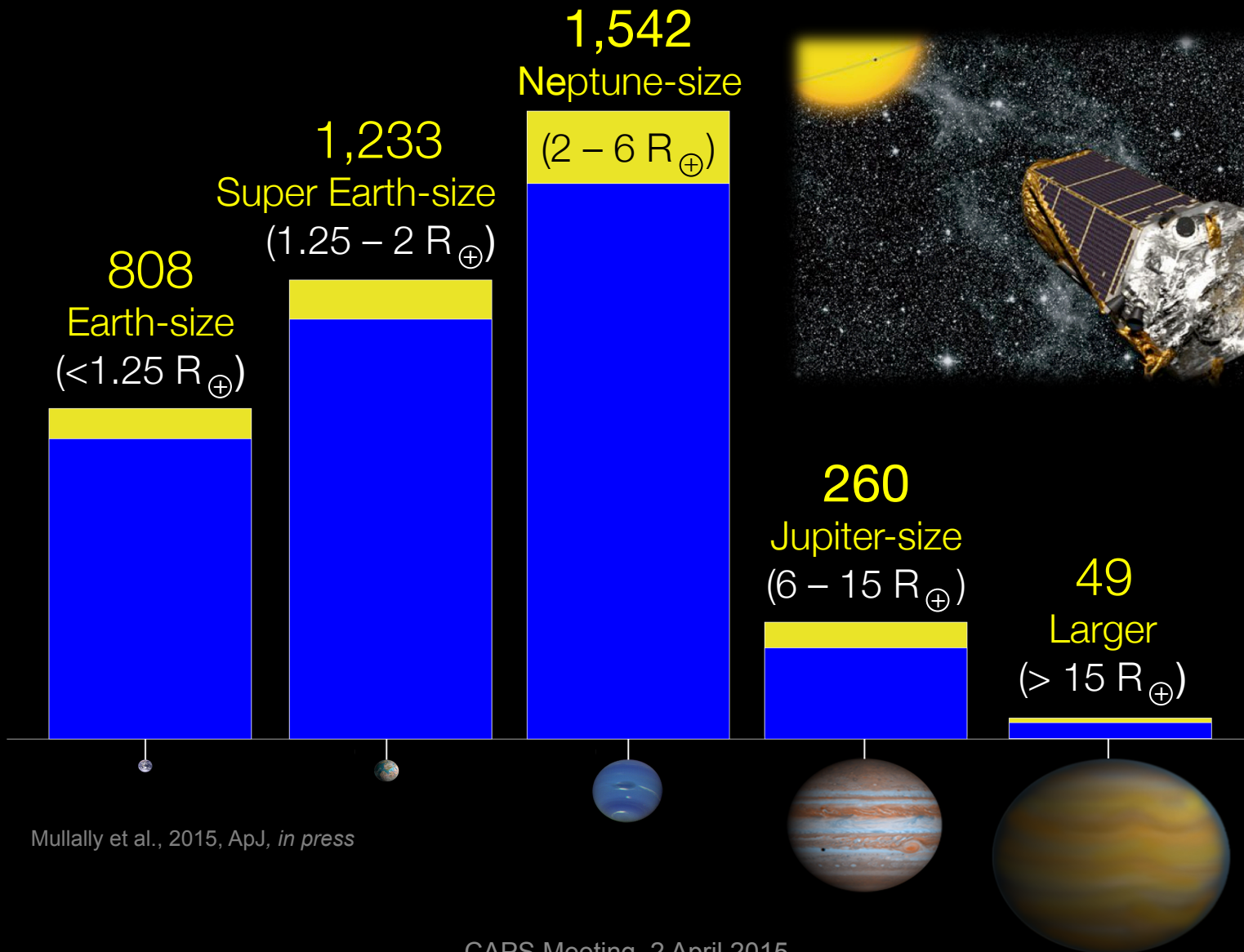


Analysis of Q1-Q16 data has revealed 554 new exoplanet candidates.

Exoplanet Exploration

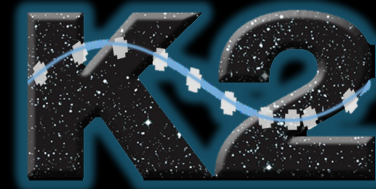


Size Distribution of Kepler Candidates

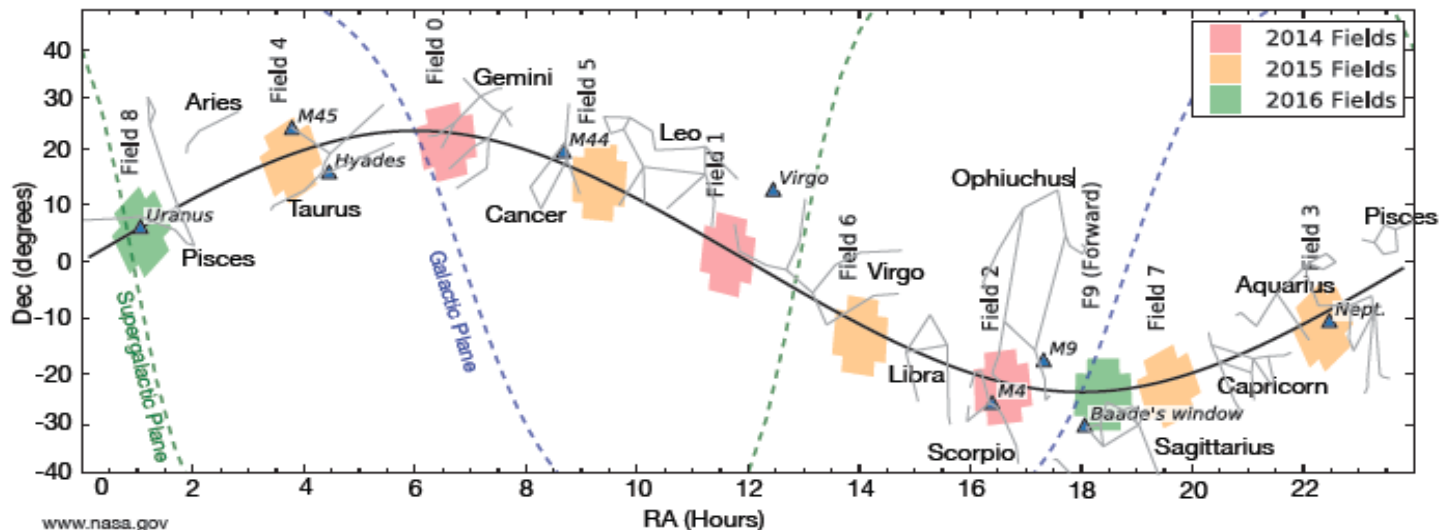




Beyond Kepler:

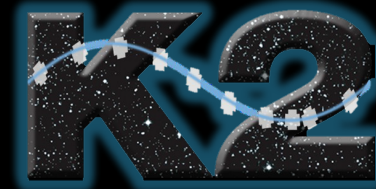


- The Kepler mission ended in May 2013 when the failure of a second of the spacecraft's 4 reaction wheels rendered it incapable of maintaining its pointing at the Kepler field.
- In response, the Kepler Project developed the “K2” mission concept—an operational strategy to repurpose the Kepler spacecraft and enable it to continue to deliver high-value science.
- By pointing the spacecraft in the ecliptic plane, it is possible to balance the solar torque around the (unstabilized) optical axis of the telescope, enabling observing campaigns of up to ~80 days.



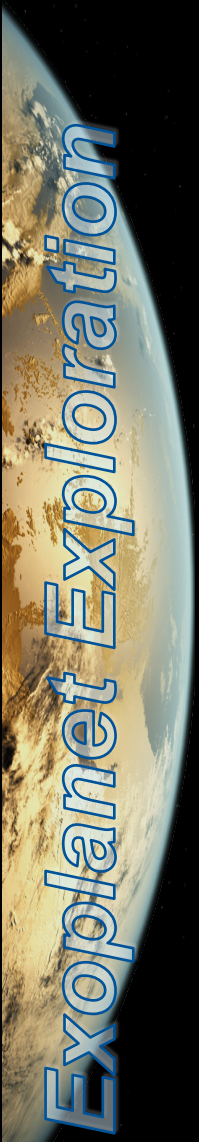


Beyond Kepler:



- The K2 mission was proposed to the 2014 Astrophysics Senior Review and subsequently recommended for continued operations through FY2016.
- Campaign 1, the first official K2 observing campaign, was initiated on 30 May 2014.
- Currently executing Campaign 4 (7 Feb. to 26 April 2015) which includes a large number of stars from the familiar Pleiades and the Hyades star clusters.
- The K2 mission is a purely community-driven mission.
 - No formal science team and no reserved targets; all targets allocated on the basis of peer-reviewed Guest Observer proposal.
 - Scope of the GO program not limited to exoplanet science.
 - Since the K2 campaign fields all lie in the ecliptic plane, proposals for Solar System science are encouraged.
 - Information about the K2 mission and GO program are available at:

<http://keplerscience.arc.nasa.gov/K2/index.shtml>





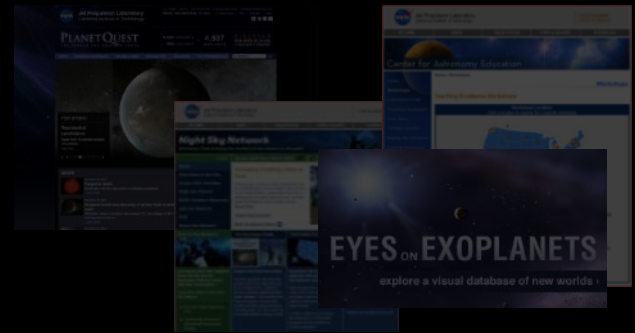
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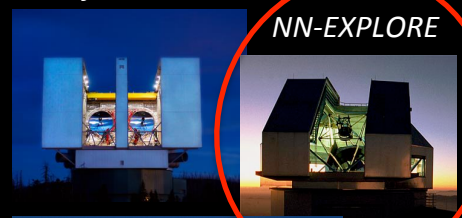
Public Engagement



Supporting Research & Technology

Mission Enabling Research

Large Binocular Telescope
Interferometer



W. M. Keck Observatory

Technology Development



High Contrast Imaging

NASA Exoplanet Science Institute





NN-EXPLORE Partnership



NASA and the NSF have teamed up to establish “**NN-EXPLORE**” – the NASA/NSF EXoPlanet Observational REsearch partnership.

- Primary objective is to enable a community-based exoplanet research program that advances NSF research interests and supports the exoplanet observations of NASA missions (e.g. K2, TESS, JWST, etc.).
- NN-EXPLORE capitalizes on the NOAO share (40%) of the observing time on the 3.5-m WIYN telescope at Kitt Peak National Observatory.
- The cornerstone of NN-EXPLORE will be a state-of-the-art extreme precision Doppler spectrometer with open access to the U.S. astronomical community (est. delivery 2018).
- Partnership commences with the WIYN 2015B observing semester, using the existing complement of instruments to conduct observations that advance NN-EXPLORE science goals.

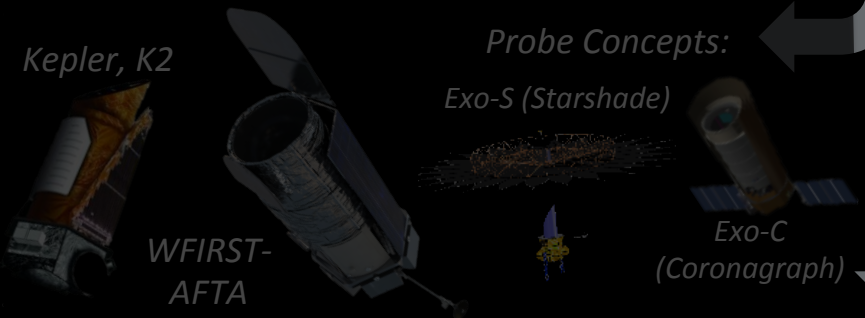




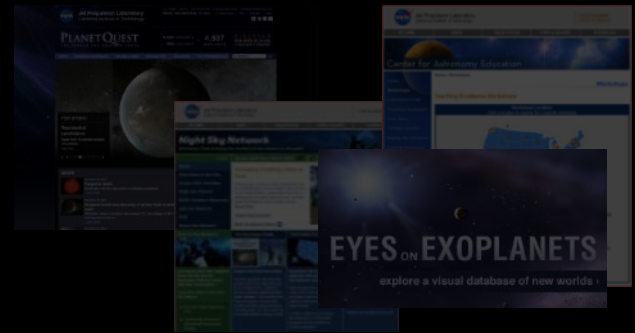
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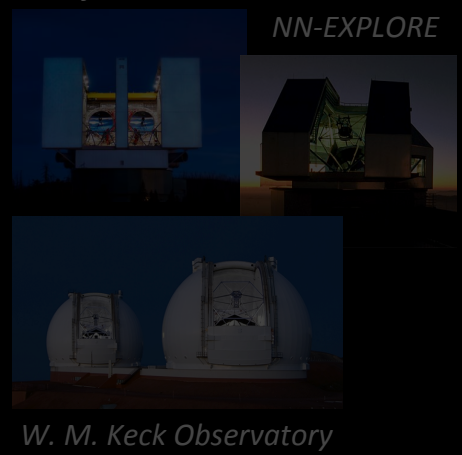
Public Engagement



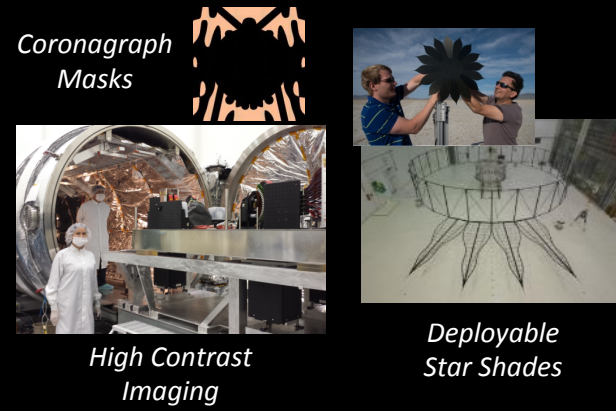
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Mission Enabling Research

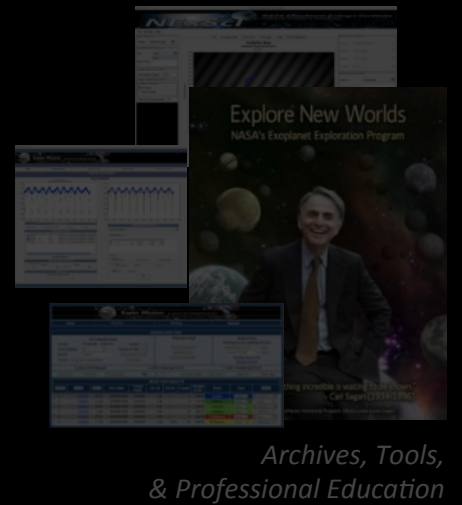
Large Binocular Telescope
Interferometer



Technology Development



NASA Exoplanet Science Institute





Meeting the Challenge of Finding Earth 2.0

- *New Worlds Technology Development Program*: The top medium-scale recommendation of the 2010 Decadal Survey of Astronomy and Astrophysics.

“The ultimate goal [of exoplanet exploration] is to image rocky planets that lie in the habitable zone—at a distance from their central star where water can exist in liquid form—and to characterize their atmospheres. To prepare for this endeavor, the committee recommends a program to lay the technical and scientific foundations for a future space imaging and spectroscopy mission.”
- Recommendation implemented through the Technology Development for Exoplanet Missions (TDEM) element of NASA’s Strategic Astrophysics Technology (SAT) program.
 - Program focused on the advancement of technologies that feed directly into the key starlight suppression techniques (coronagraphy, starshades) that will enable a future strategic exo-Earth direct detection and characterization mission.
 - Goal is to enable systems capable of delivering contrast ratios of better than 1×10^{-10} at the angular separation of the habitable zones around stars within ~50 light years of the Sun.

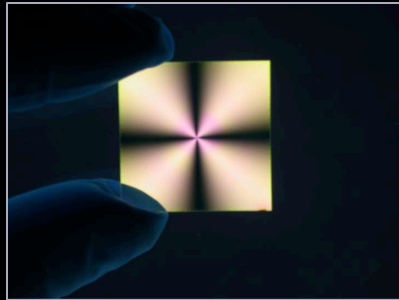
Exoplanet Exploration



Coronagraph Technology Development

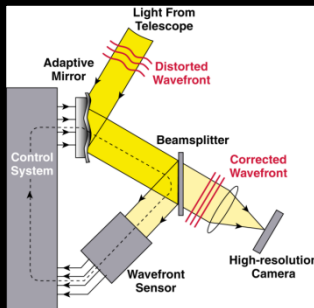
Exoplanet Exploration

Occulting Masks/ Apodizers

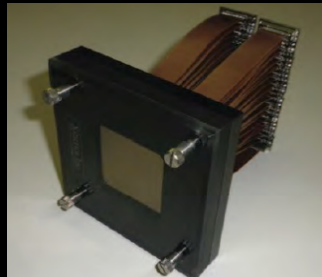


Serabyn – Vector Vortex Mask

Low Order Wavefront Sensing and Control

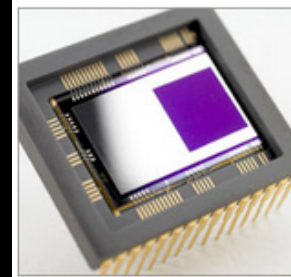


Deformable Mirrors



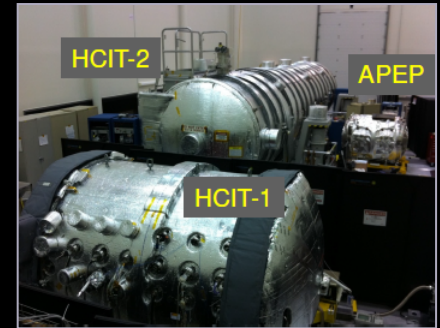
Xinetics

Ultra-Low-Noise Visible Detectors



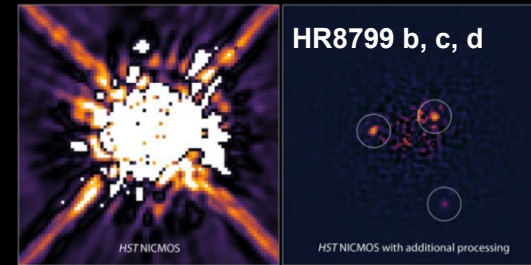
e2v Electron Multiplying CCD

System Demonstration



Jet Propulsion Laboratory

Image Post Processing



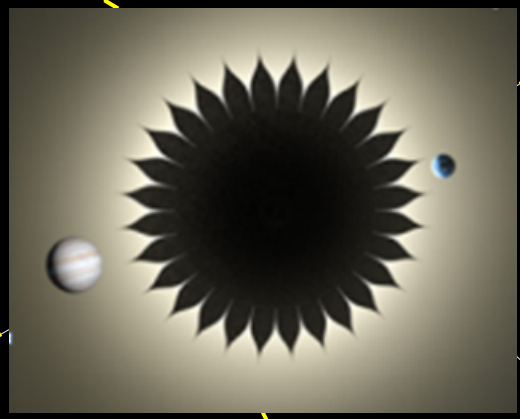
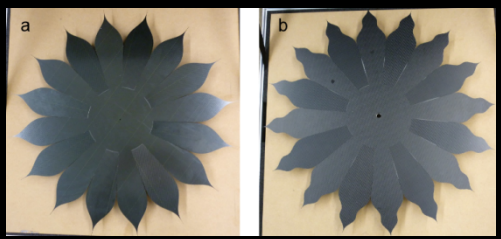
Soumer et al. 2011



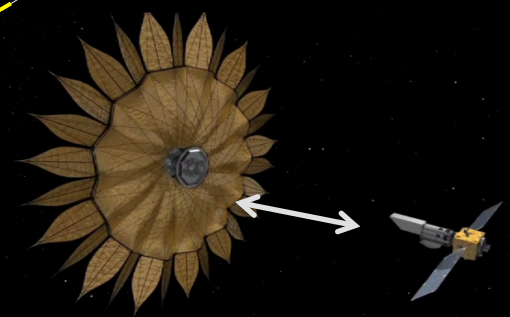
Starshade Technology Development

Exoplanet Exploration

Control of Scattered Light



Formation Flying

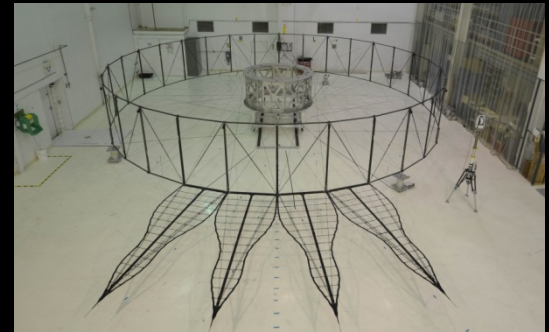


Validation of Optical Models



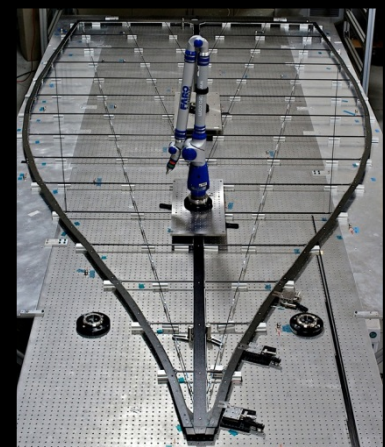
NGAS

Starshade Deployment



NGAS, Princeton, JPL

Petal Prototypes



Princeton, JPL



COMMUNITY ENGAGEMENT

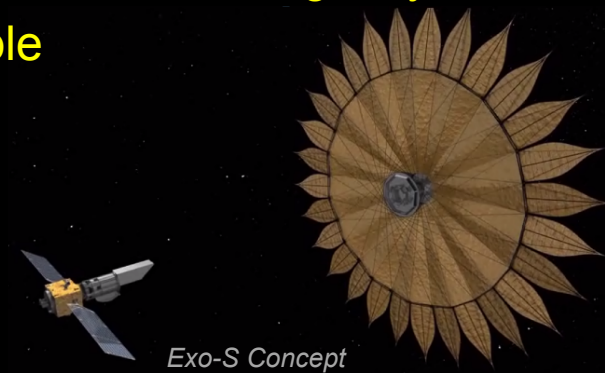
NASA's Exoplanet Exploration Program relies on input from the scientific community

Exoplanet Exploration



Channels for Community Involvement

- Exoplanet Program Analysis Group (ExoPAG)
 - Provides an open forum for community input into the development and execution of NASA's Exoplanet Exploration Program.
- Competed Research and Technology Development Programs
- Mission concept study teams
 - WFIRST-AFTA – Implementation of the top-rated Large-scale space mission of the 2010 Astrophysics Decadal Survey using one of two 2.4-m space telescopes obtained by NASA from another Federal agency.
 - Exo-C, Exo-S – Concept studies of two possible probe-class (< \$1B lifecycle cost) exoplanet direct imaging missions using an internal coronagraph (Exo-C) or a starshade (Exo-S).
- Exoplanet Technology Assessment Committee (ExoTAC)
 - Panel of independent scientists and technologists that provide independent oversight of technology development programs conducted under the auspices of the Exoplanet Exploration Program.



Exo-S Concept



ExoPAG Overview

- The ExoPAG is an open, community-based forum for soliciting and coordinating community input and analysis into the development and execution of NASA's Exoplanet Exploration Program.
 - Brings specialized expertise to bear on issues relating to NASA's Exoplanet Exploration Program;
 - Provides a conduit for keeping community informed about program activities.
- Biannual meetings generally held in conjunction with major science conferences to facilitate stakeholder participation
 - Winter AAS Meetings
 - Other conferences to expand involvement across the program's diverse group of stakeholders (e.g. DPS Meetings, AbSciCon 2015)
- Chair: A. Boss, Carnegie Institution of Washington
 - Chair supported by a 10-member Executive Committee with a rolling membership, each of whom serve 3-year terms.
 - Open call nominations for the ExoPAG EC issued annually.
- Web Site: <http://exep.jpl.nasa.gov/ExoPAG/>

Exoplanet Exploration



NASA Exoplanet Systems Science

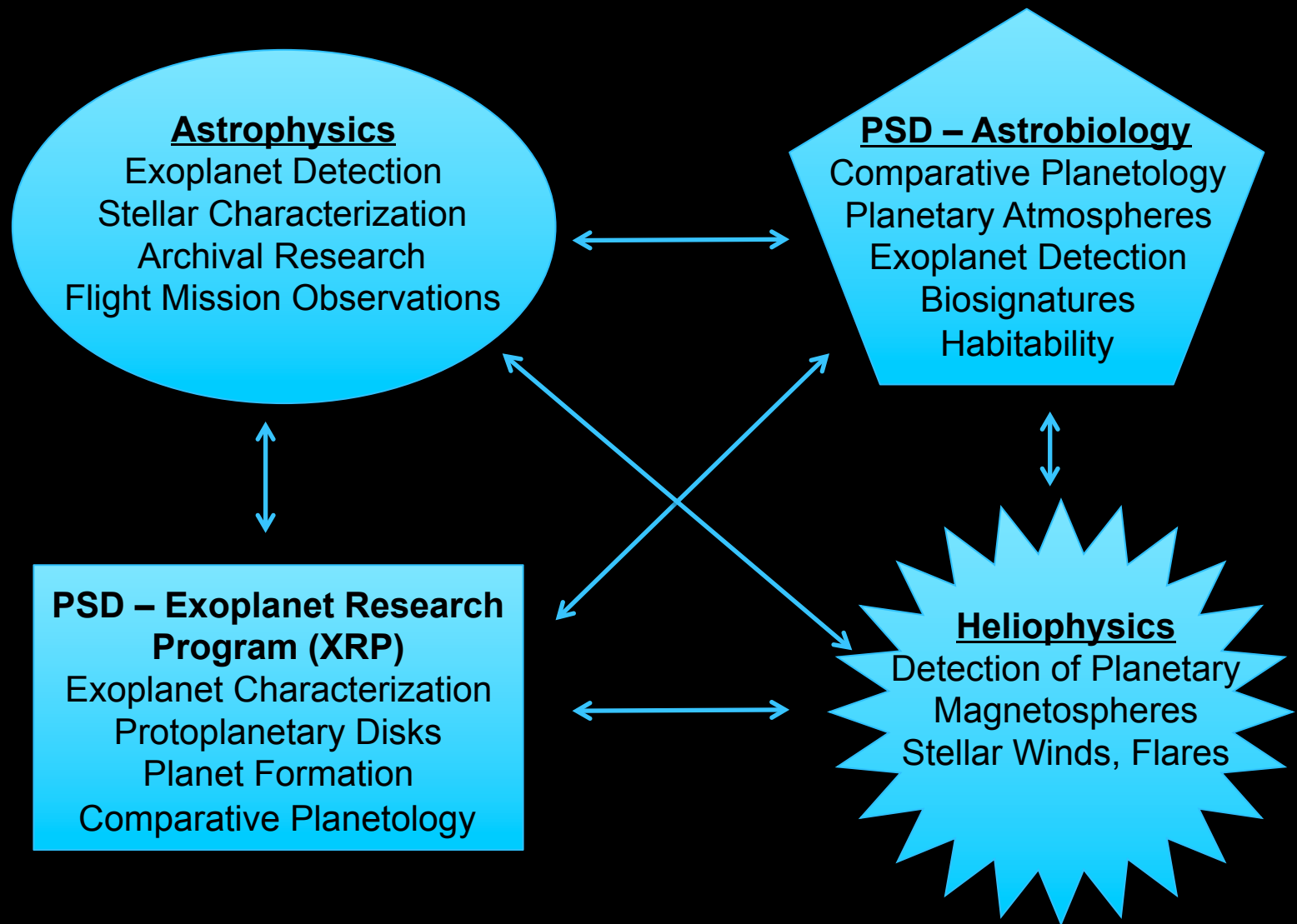
NASA Exoplanet Systems Science, or NExSS, is a cross-division initiative to establish a research coordination network with the objectives:

- To further our joint strategic objective to explore exoplanets as potential habitable and inhabited worlds outside our solar system.
- To leverage existing Programs in SMD to advance the field of Exoplanet Research, specifically research in comparative planetology, biosignature and habitat detection, and planet characterization.
- To establish a mechanism to break down the barriers between, divisions, disciplines and stove piped research activities.

Exoplanet Exploration



Implementation



Exoplanet Exploration



Exoplanet R&TD Opportunities

- **Exoplanet Research Program (XRP)**
Joint program with Planetary Science Division. Supports scientific investigations into the composition, dynamics, energetics, and chemistry of extrasolar planets, and the detection and characterization of other planetary systems.
- **Astrophysics Research and Analysis (APRA)**
Supports development of technologies and instruments that will enable future exoplanet flight missions and measurements, as well as suborbital and suborbital-class exoplanet investigations.
- **Strategic Astrophysics Technology Program (SAT)**
Supports mid-TRL maturation of technologies that feed directly into the key starlight suppression techniques (coronagraphy, starshades) that will enable a future strategic exo-Earth direct detection and characterization mission.
- **Astrophysics Data Analysis Program (ADAP)**
Supports archival research based on publicly-available data from NASA missions.

Exoplanet Exploration



Where will Exoplanet Exploration take us in 100 years?

Let's call the *Exoplanet Travel Bureau*, and book a trip...

Exoplanet Exploration

