



**Jet Propulsion Laboratory**  
California Institute of Technology

# NASA's Exoplanet Exploration Program Updates

Gary Blackwood, Program Manager

ExoPAG 13, January 3, 2015

227<sup>th</sup> Meeting of the AAS, Kissimmee FL

# NASA Exoplanet Exploration Program



## Purpose described in 2014 NASA Science Plan

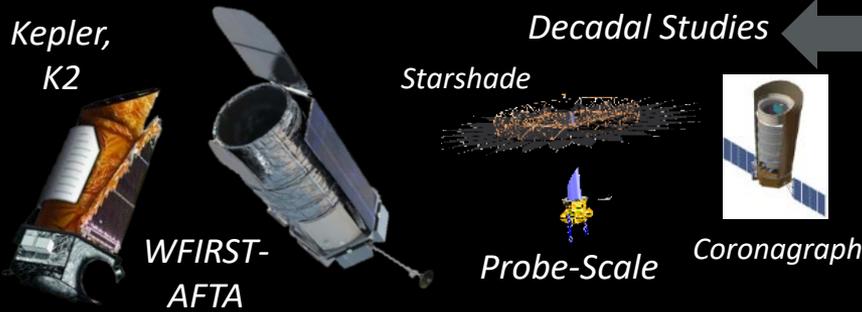
1. Discover planets around other stars
2. Characterize their properties
3. Identify candidates that could harbor life

*The Search for Life in our Galaxy*

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

# NASA Exoplanet Exploration Program

## Space Missions and Mission Studies



## 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 Star Shades

### NASA Exoplanet Science Institute

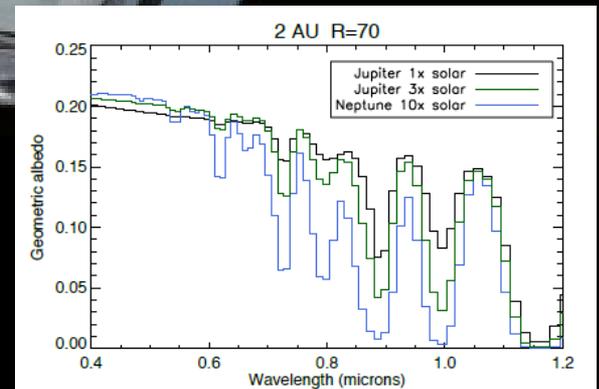
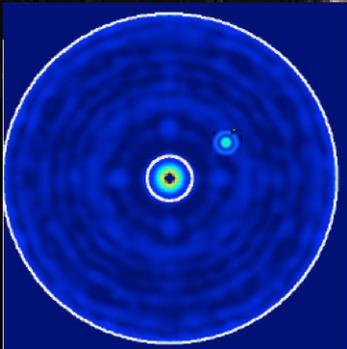
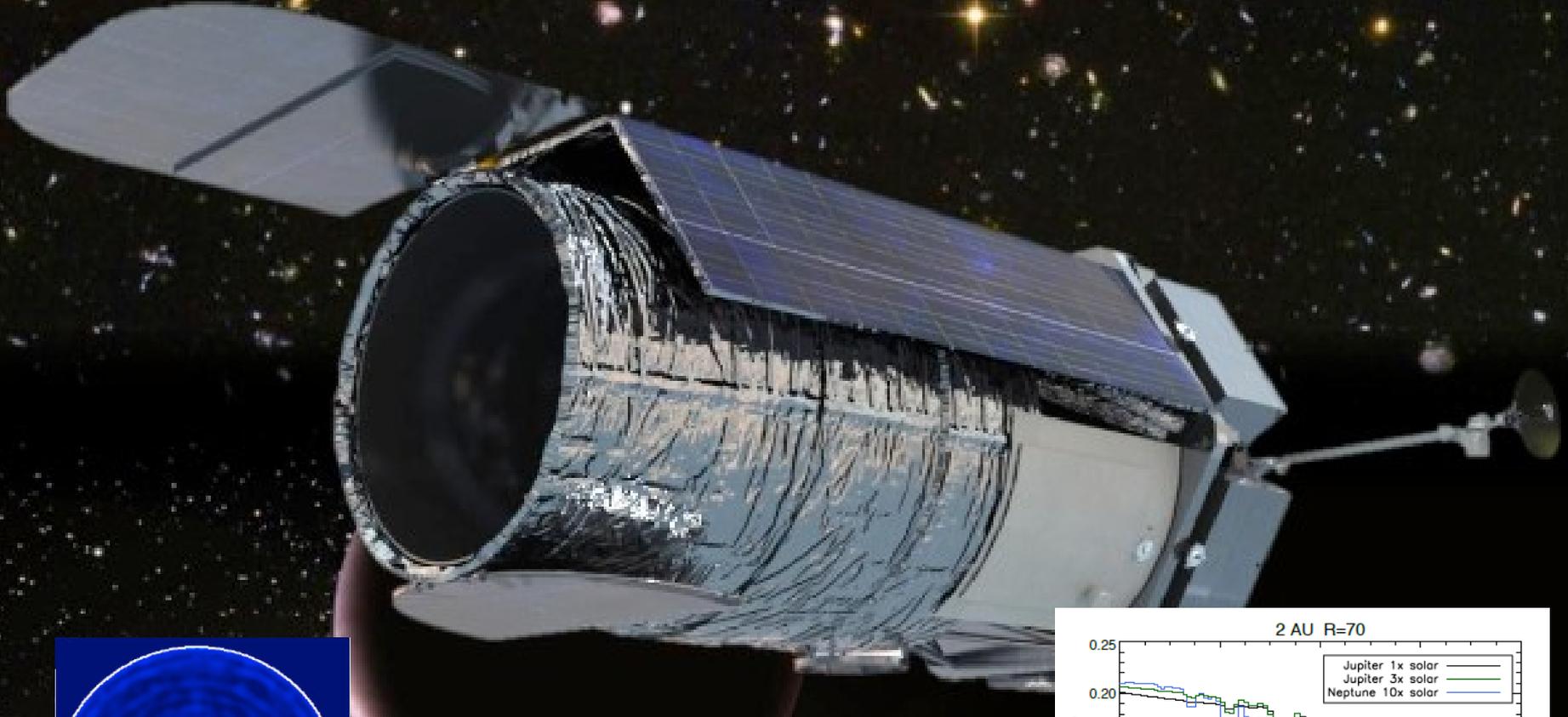


Archives, Tools, Sagan Fellowships, Professional Engagement

# Progress from Astro2010 towards Next Decadal Survey

# WFIRST / AFTA

Dark Energy, IR Survey, Exoplanet Census, Imaging and Spectroscopy



# WFIRST / AFTA

- WFIRST technology (Coronagraph and IR detectors): All planned milestones successfully completed.
- Complete latest design cycle (L2 orbit) – basis for Mission Concept Review (MCR) design reference.
- Successfully held Mission Concept Review (MCR) 12/8-9
- FY16 Omnibus Appropriations Bill: \$90M for WFIRST
- WFIRST Formulation Science Team Announced: ten Science Investigation Teams (SITs) and two Adjutant Scientists: D. Spergel (Widefield) and J. Kasdin (Coronagraph).
- 12/18: Notice provided by GSFC for Wide Field Instrument Industry four-month Concept Study
- NASA Key Decision Point (KDP)-A planned for 2/17: Agency approval to enter Formulation



# Kepler Close Out

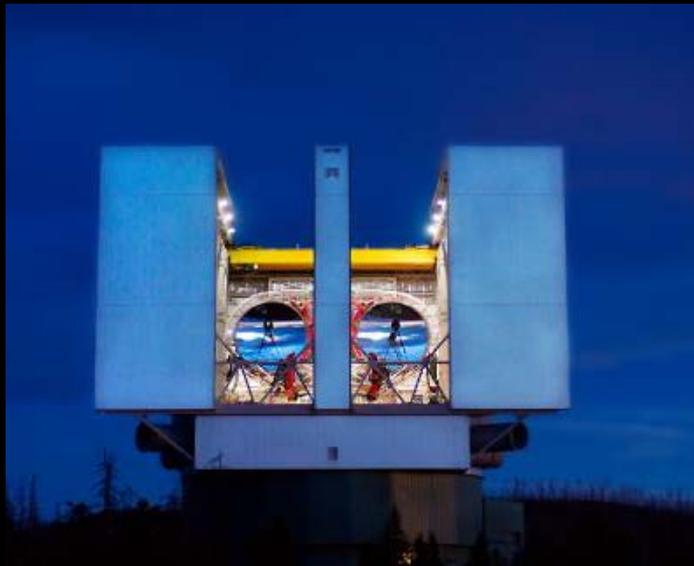
- Big news last summer: Kepler 452b
- Held successful Hack Week (Oct 2016). 36 actionable recommendations
- Kepler closeout and final data processing continues steadily within overall schedule margin.
  - Level 1 milestones completed since last ExoPAG:
    - SOC 9.3 Q0-Q17 Long Cadence Light Curves to MAST
    - Completed Pipeline Development for SOC 9.3
    - SOC 9.2 Final Occurrence Rate Products
    - Closed SOC 9.2 Q1-Q17 Activity Table
  - Final data processing (SOC 9.3) underway; on track for
    - SOC 9.3 Q0-Q17 Short Cadence Light Curves to MAST (May 2016)
    - Documentation Completeness Review (Oct 2016)
    - SOC 9.3 Final Occurrence Rate Products (April 2017)



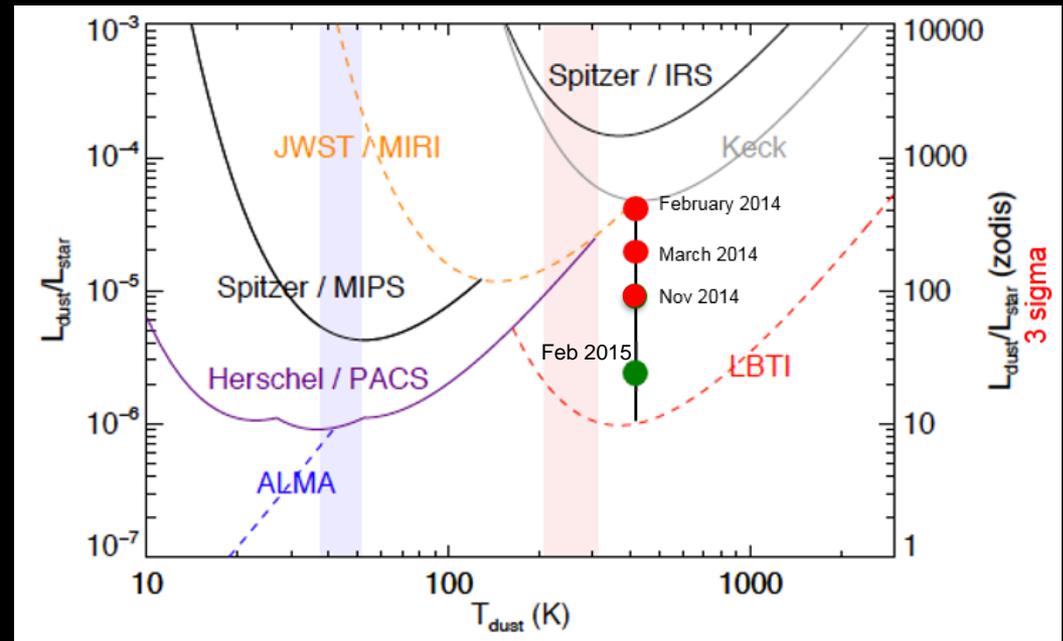
# Large Binocular Telescope Interferometer

Measures exozodiacal dust in habitable zones

Phil Hinz, PI



## LBTI Performance



- Demonstrated 12 zodi sensitivity for a solar twin at 10 pc at May 2015, <6 zodi single star sensitivity planned for April 2016 Science Operations Review
- Commissioning/HOSTS survey interrupted by glycol leak in secondary mirror but repairs are nearly complete and binocular operation will restart January 2016
- Plan for 32 star survey giving <2 zodi mean uncertainty over survey population
- Results of HOSTS survey to inform next decadal survey on direct exoplanet imaging



- **Scope:**

- Ongoing Guest Observer program using NOAO share of telescope time for exoplanet research
- Extreme precision radial velocity spectrometer for WIYN telescope is in procurement

- Downselect of competing proposals March 18
- Winning team will be invited to deliver telescope port adapter
- Instrument to be commissioned by July 2019



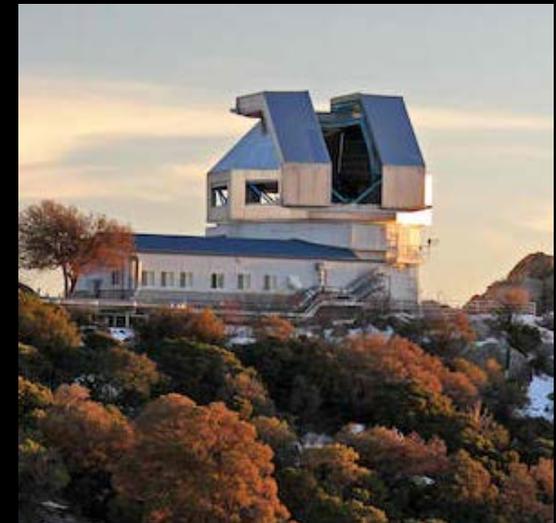
PI: G. Furesz



PI: S. Mahadevan

- **Motivation**

- 2010 Decadal Survey calls for 0.1-0.2 m/s precise ground-based spectrometer for exoplanet discovery and characterization
- Follow-up of current missions (K2, TESS, JWST, WFIRST)
- Pathfinder observations inform design/operation of future missions

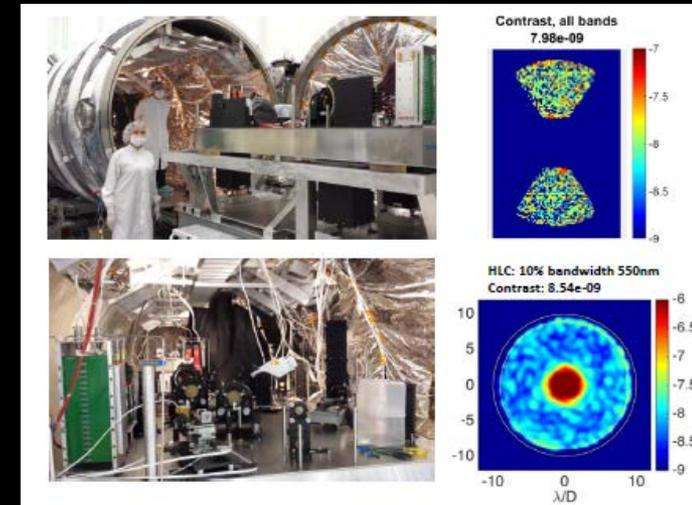
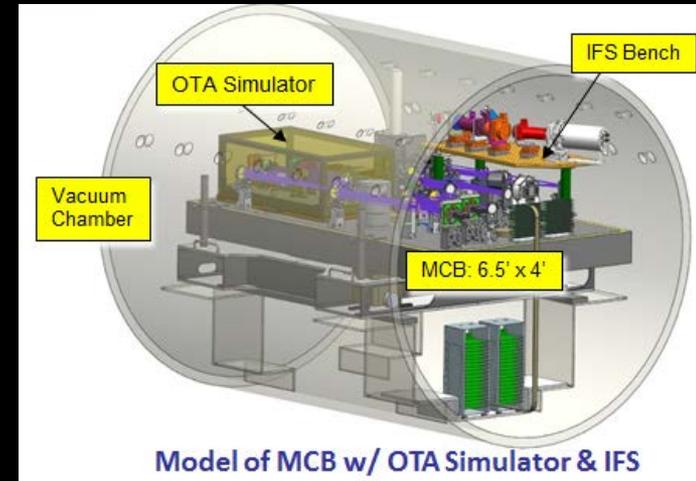


3.5m WIYN Telescope  
Kitt Peak National Observatory  
Arizona

# Technology - Coronagraph

All WFIRST technology milestones met on schedule

- Delivered a modelable coronagraph bench to WFIRST Coronagraph team
- Demonstrated broadband (10% at 550nm) high raw contrast ( $<1e-8$ ) in a static environment for both
  - HLC (Hybrid Lyot Coronagraph)
  - SPC (Shaped-Pupil Coronagraph) with WFIRST telescope pupil
- Demonstrated low-order wavefront error sensing and close-loop tip/tilt correction ( $<0.4$  mas rms per axis)
- Next: milestones for detector, PIAACMC, coronagraph raw contrast in dynamic environment



# Technology - TDEM

Reports for completed and active: <http://exep.jpl.nasa.gov/technology/>

- Active TDEM

- 2010

- (Bierden) Environmental Testing of MEMs DMs
    - (Helmbrecht) Environmental Testing of MEMs DMs
    - (Lyon) Visible Nulling Coronagraph Testing

- 2012

- (Casement) Starshade Edge Scattering
    - (Kasdin) Optical and Mechanical Verification of External Occulter

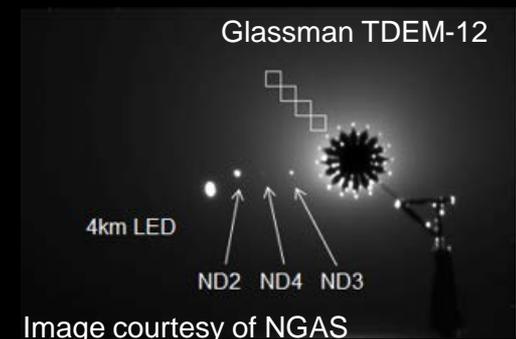
- 2013

- (Bendek) Enhanced Direct Imaging with Astrometric Mass
    - (Cash) Development of Formation Flying Sensors
    - (Kasdin) Formation Flying of External Occulters
    - (Lyon) Segmented Aperture Nulling Coronagraph

- New TDEM

- 2014

- (Thomson) Starshade Optical Shield
    - (Bolcar) Next Generation Visible Nulling
    - (Serabyn) Broadband Vector Vortex Coronagraph



# Preparations for Next Decadal Survey

# Other Program Updates

# Kepler K2



- Add some K2 science from Steve
- Spacecraft is healthy: completed campaign 7 Deep Space Network (DSN) downlink and began campaign 8 (Jan 3)
- Since last ExoPAG, data released for campaigns 3, 4, 5, ...6?
- Looking forward to Campaign 9 (galactic bulge, microlensing), ukirt?
- Preparing senior review proposal
- Estimate: sufficient fuel for 17 campaigns
- 32 K2 exoplanets have been confirmed, and dozens (soon to be hundreds) of exoplanet candidates
- 6 of the confirmed exoplanets are potentially rocky and suitable for atmospheric characterization by JWST
- In 2015, the scientific community added a record 453 scientific papers related to the spacecraft. See <http://keplerscience.arc.nasa.gov/publications.html>



**Jet Propulsion Laboratory**  
California Institute of Technology



National Aeronautics and  
Space Administration

Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, California

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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
  - Northrop Grumman Aerospace Systems
  - National Optical Astronomy Observatory (NOAO)  
<http://www.noao.edu/news/2015/pr1502.php>
  - Massachusetts Institute of Technology
  - Penn State University

# Exoplanet Missions



W. M. Keck Observatory



Large Binocular Telescope Interferometer



NN-EXPLORE

## Ground Telescopes with NASA participation

<sup>1</sup> NASA/ESA Partnership  
<sup>2</sup> CNES/ESA

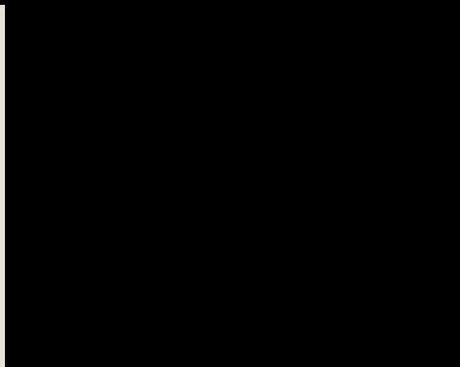
# Where will exploration take us in 100 years? Introducing the *Exoplanet Travel Bureau*

*Exoplanet Travel Bureau*

EXPERIENCE THE GRAVITY OF **HD 40307g** A SUPER EARTH

The path traveled in its orbit around HD 40307 g is about twice the volume of Earth and eight times more massive, making it something to behold. A "super-Earth" and a "mini-Neptune". Planets of these categories were first discovered by the Kepler mission. A secondary reason that suggests our galaxy contains an abundance of such worlds. The "big one" between Jupiter and Saturn and our knowledge will still understand at the point, so the planet itself may be located, as depicted here, in a more habitable world of gas and ice.

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RELAX ON **KEPLER 16b**

THE LAND OF TWO SUNS  
WHERE YOUR SHADOW ALWAYS HAS COMPANY

Like the Kepler-16 system, Kepler 16b is a pair of stars at a very close distance, about 8 times further from the center of the star pair than the stars are from each other. Classified first as a terrestrial planet, Kepler 16b is thought to be a gas giant like Saturn. Prospects for life on this unusual world aren't good, as there is no atmosphere similar to that of dry ice. But the discovery indicates that the mystery is never solved by anything but science fiction.

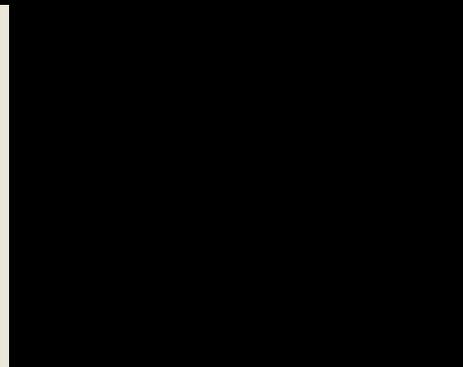
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*Exoplanet Travel Bureau*

**Kepler-186f**  
WHERE THE GRASS IS ALWAYS REDDER ON THE OTHER SIDE

Kepler 186f is the first Earth-size planet discovered in the primary habitable zone around another star, where liquid water could exist on the planet's surface. It was a rocky world and smaller than our Earth. Despite its size and its place in the Kepler 186, its photosphere could have been influenced by the star's red outburst activity, making for a color palette that's very different from the greens on Earth. This discovery was made by Kepler. NASA's planet-hunting space telescope.

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VISIT THE PLANET WITH NO STAR

**PSO J318.5-22**  
WHERE THE NIGHTLIFE NEVER ENDS!

Discovered in October 2015 using direct imaging, PSO J318.5-22 belongs to a special class of planets called rogue, or free-floating, planets. Wandering alone in the galaxy, they do not orbit a parent star. Not much is known about how these planets come to exist, but conventional wisdom had they may be where "dark stars" or planets ejected from very young systems after an interaction with another planet. These rogue planets glow faintly from the heat of their formation. Only free-floating ones, they will be drifting in the dark. Confirmed and candidate exoplanets and all available data are listed in the NASA Exoplanet Archive.

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# New Exoplanet Travel Bureau poster: “Greetings From Your First Exoplanet”



ExoPlanet Exploration Program



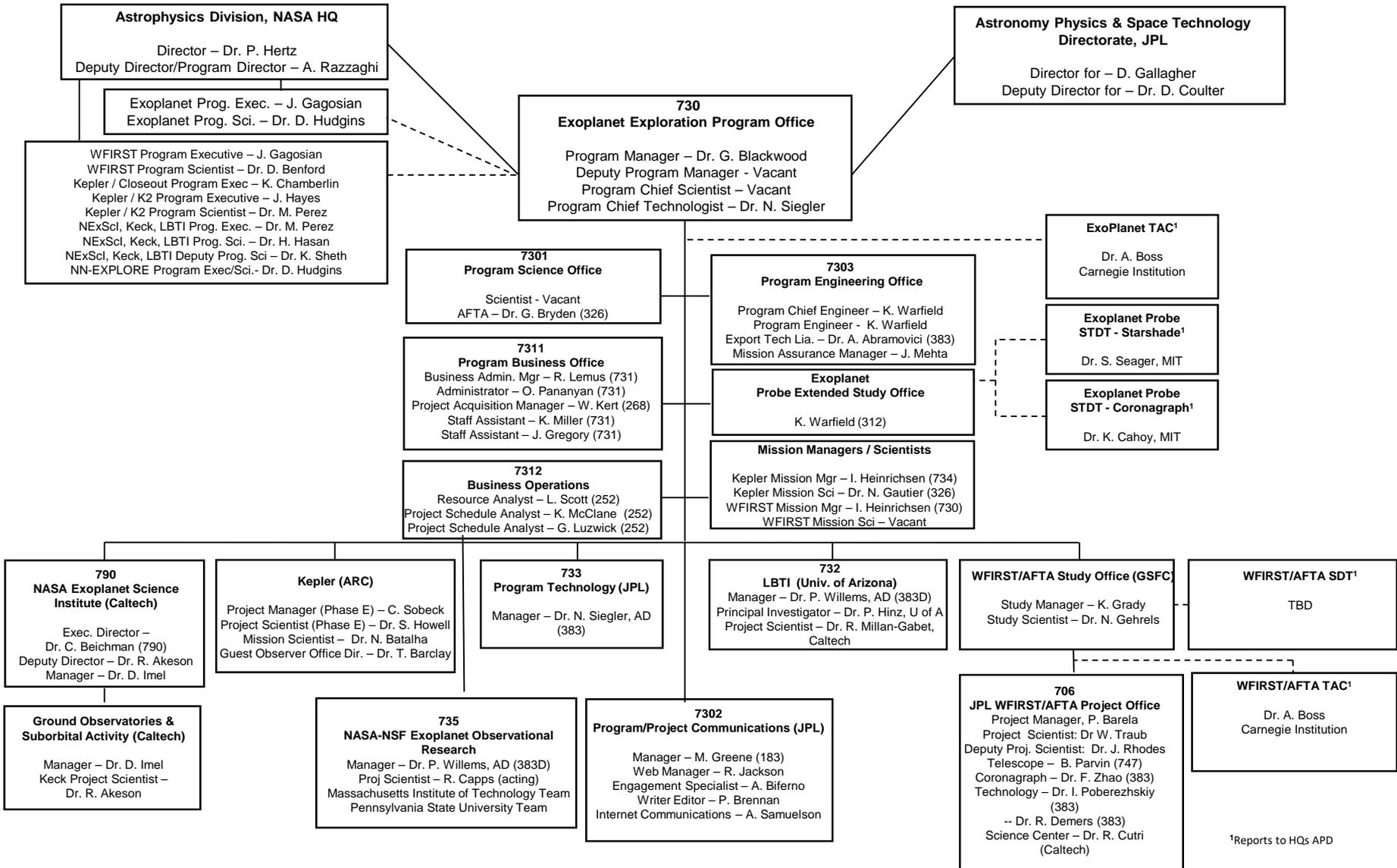
The fifth poster in the Exoplanet Travel Bureau series was released on October 20<sup>th</sup> in conjunction with the 20<sup>th</sup> Anniversary activities

*Text of poster:*

*Greetings From Your First Exoplanet:*

*“While there is much debate over which exoplanet discovery is considered the “first,” one stands out from the rest. In 1995, scientists discovered 51 Pegasi b, forever changing the way we see the universe and our place in it. The exoplanet is about half the mass of Jupiter, with a seemingly impossible, star-hugging orbit of only 4.2 Earth days. Not only was it the first planet confirmed to orbit a sun-like star, it also ushered in a whole new class of planets called Hot Jupiters: hot massive planets orbiting closer to their stars than Mercury. Today, powerful observatories like NASA’s Kepler space telescope will continue the hunt of distant planets.”*

# Exoplanet Exploration Program Organization Chart



¹Reports to HQs APD

# NExSci Sagan Fellowships

## Technical

CM-2	CM-1	CM
G	G	G

## Schedule

CM-2	CM-1	CM
G	G	G

## Resources

CM-2	CM-1	CM
G	G	G

## Programmatic

CM-2	CM-1	CM
G	G	G

## Overall

CM-2	CM-1	CM
G	G	G

- By the Nov 5 deadline, NExSci received 89 compliant\* applications for the 2016 class of Sagan Fellows. The review panel will meet early in January 2016

\*Two applications were non-responsive

- Next year's Sagan Summer Workshop will be during the week of July 18. Proposed topic: "Is there an exoplanet in my data?"



*NExSci hosted the 2015 Sagan Summer Workshop: "Exoplanet System Demographics: Theory and Observations" on the Caltech campus, with over 140 participants*