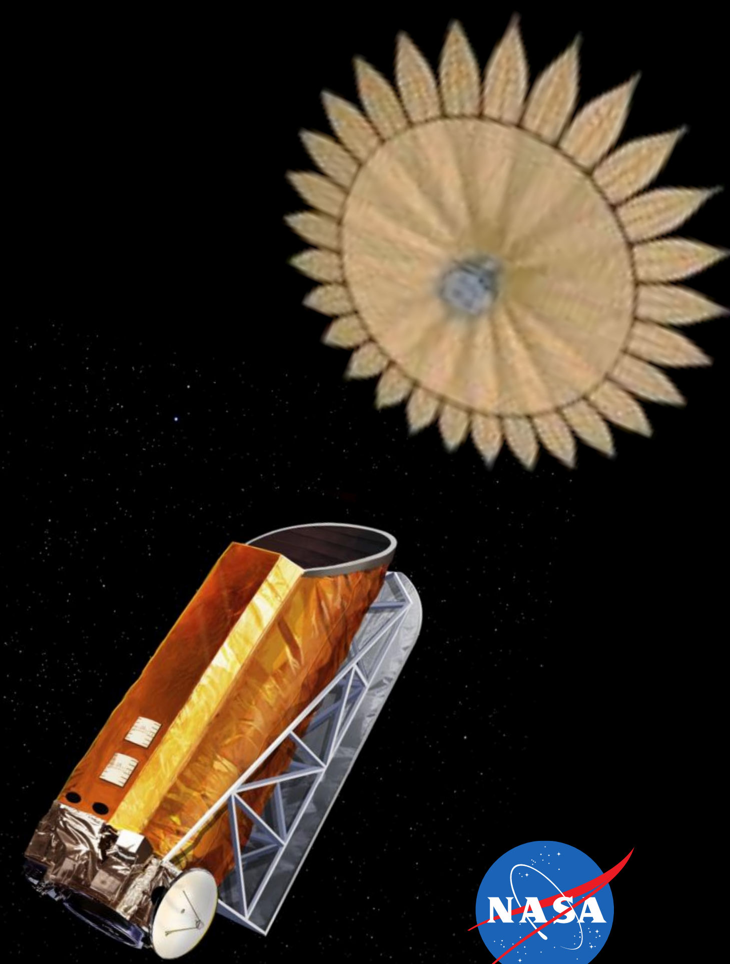
Science Opportunities with 1 m class Space Telescopes



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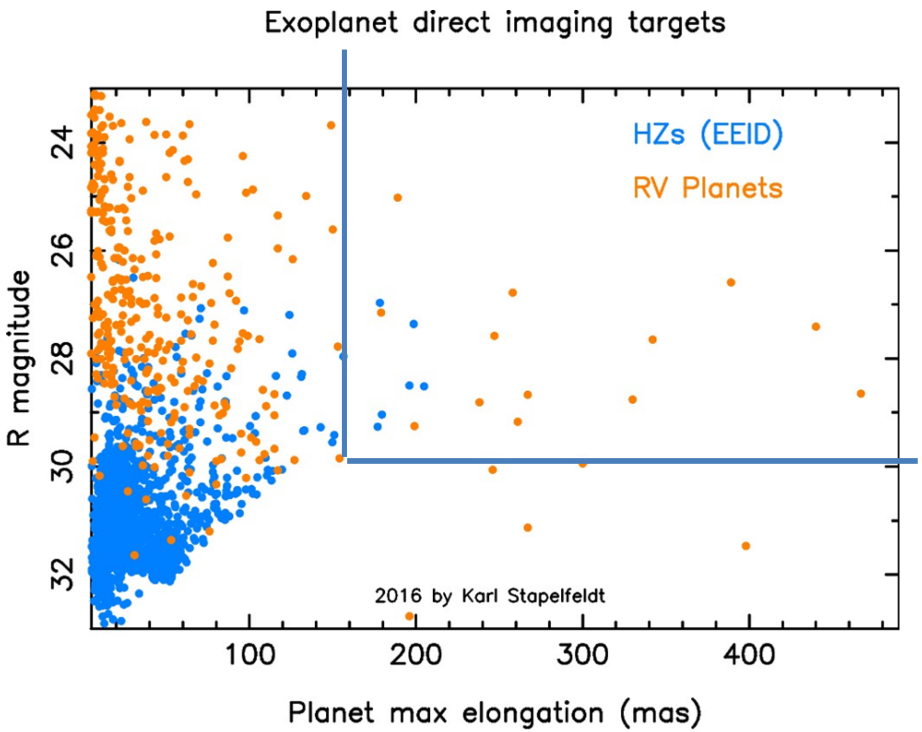
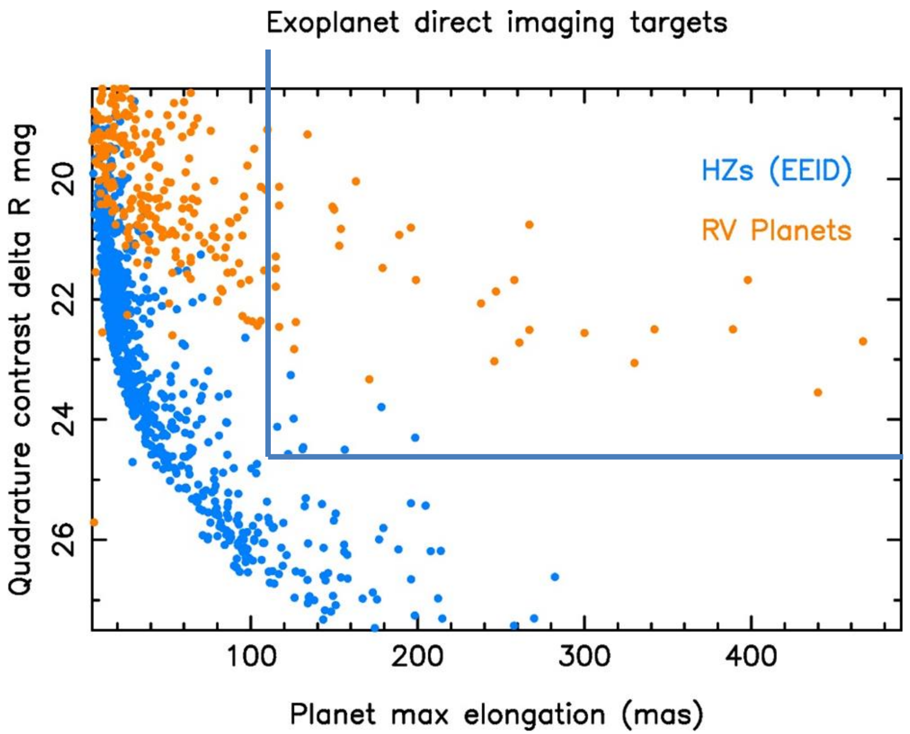
Chair, Exo-C STDT during 2013-2015 at
NASA Goddard Space Flight Center

Clearance #18-1725
Pre-decisional information for planning and discussion only

Government sponsorship acknowledged

Exoplanet targets by brightness, contrast





Context for Exoplanet Probe Studies

- After Astro2010 NASA conducted five "probe" mission studies to investigate science available at the ~$1B cost level
- *Kepler* mission results strongly motivate an exoplanet direct imaging follow-on mission, particularly for super Earths & mini-Neptunes
- Flagship mission for spectroscopy of ExoEarths requires 10^{-10} contrast (> 10^5 times beyond HST performance), aperture size ≥ 4 m
- Modest ~1 m aperture missions would access small samples of bright/nearby planets and are a natural first step technologically
  - Spectroscopy of larger exoplanets & disk imaging can be done with coronagraph at 10^{-9} contrast with a ~1.5 m telescope
  - Starshade would allow ~ 2 dozen nearby HZs to be accessed by a 1.1 m
- Coronagraph "Exo-C" and starshade "Exo-S" probe studies took place over 2013-2015 as potential backups to WFIRST
- https://exoplanets.nasa.gov/exep/studies/probe-scale-stdt/

Sm… …pts

Table F-1. His… …issions.

Mission	…	Study Lead
CIT		
CODEX		
ECLIPSE		
ECLIPSE		
ESPI		
JPF		
ECLIPSE		
EPIC		
ECLIPSE		
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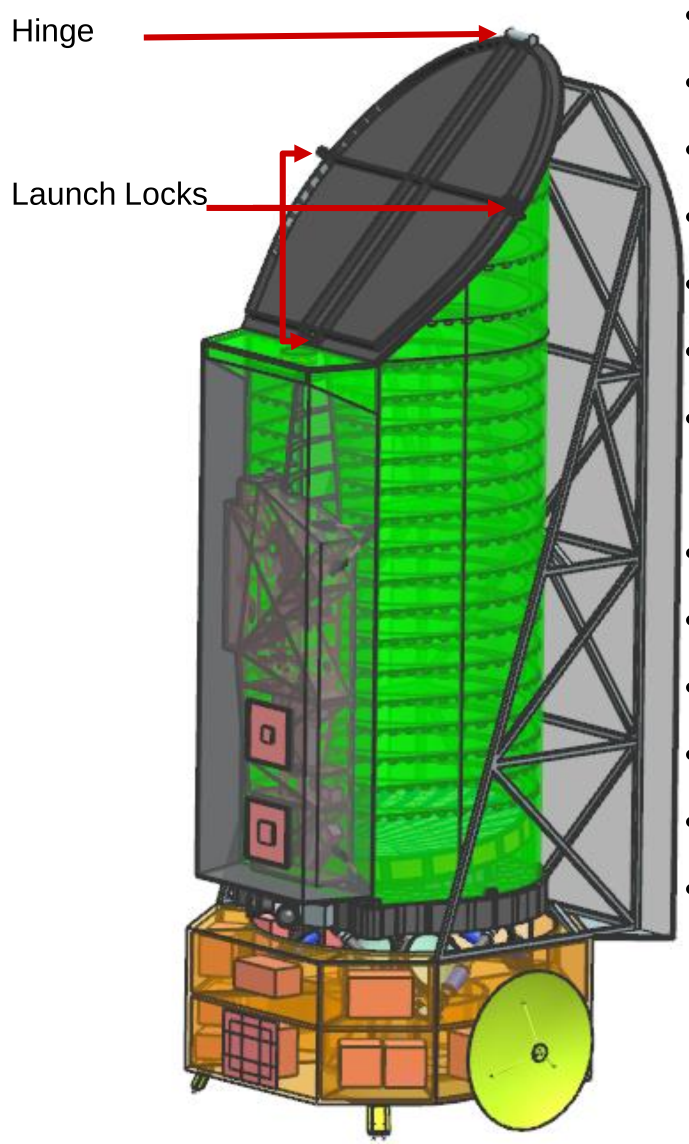
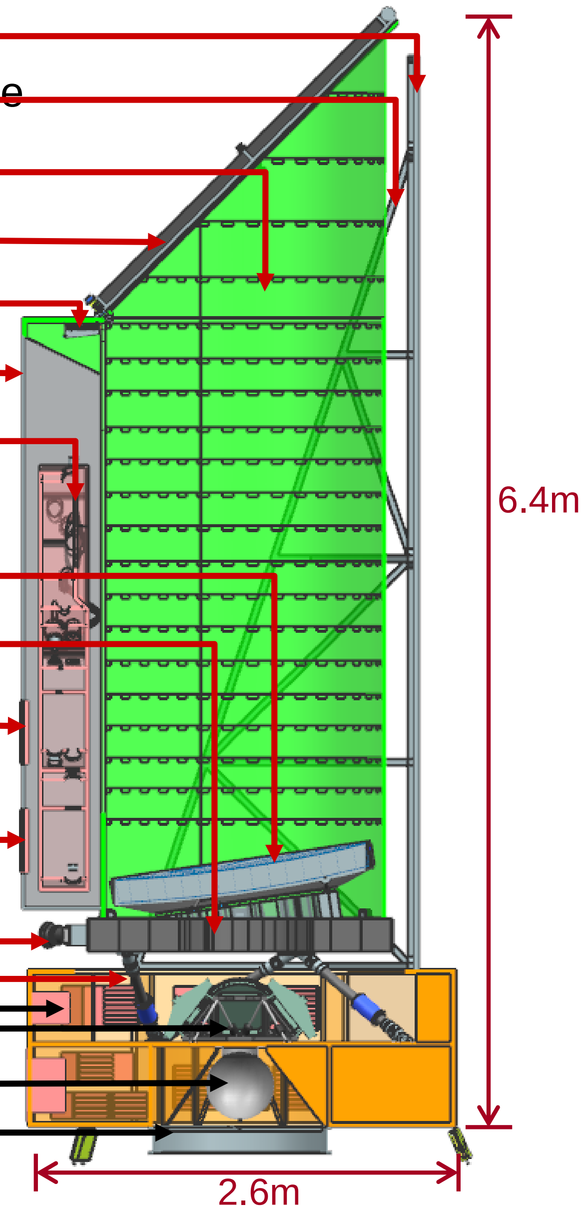
Exo-C Mission Concept



- Solar Array/Sunshade
- SA/Sunshade Support Structure
- Barrel Structure
- Removable Lid
- Secondary Mirror Assy
- Instrument Enclosure
- Instrument Bench Assy
- Primary Mirror Assembly
- Primary Support Structure
- Radiator Panel Assembly
- Star Tracker Assembly
- Isolation Assembly
- Spacecraft Assembly
  - SC and Payload Electronics
  - Reaction Wheel Assy
  - Propulsion Assy
  - LV interface Ring Assy



Predecisional information, for planning and discussion only

Exo-C Technical Capabilities

ExEP

Telescope primary mirror	1.4 m diameter
Uncontrolled speckle contrast	10^{-9} raw at IWA, better further out
Contrast stability	10^{-11} at IWA 2 hours after slew/roll
Spectral coverage	450–1000 nm
Spectral resolution λ > 500 nm	R = 70
Inner Working Angle (IWA) 2 λ/D	0.16″ @ 500 nm, 0.24″ @ 800 nm
Outer Working Angle ~ 20 λ/D	2.6″ @ 800 nm
Spillover light from binary companion	3×10^{-8} raw @ 8″, TBD additional reduction from wavefront control
Astrometric precision	< 30 milliarcsec
Fields of view	42″ imager, 2.2″ spectrograph
Mission lifetime	3 years

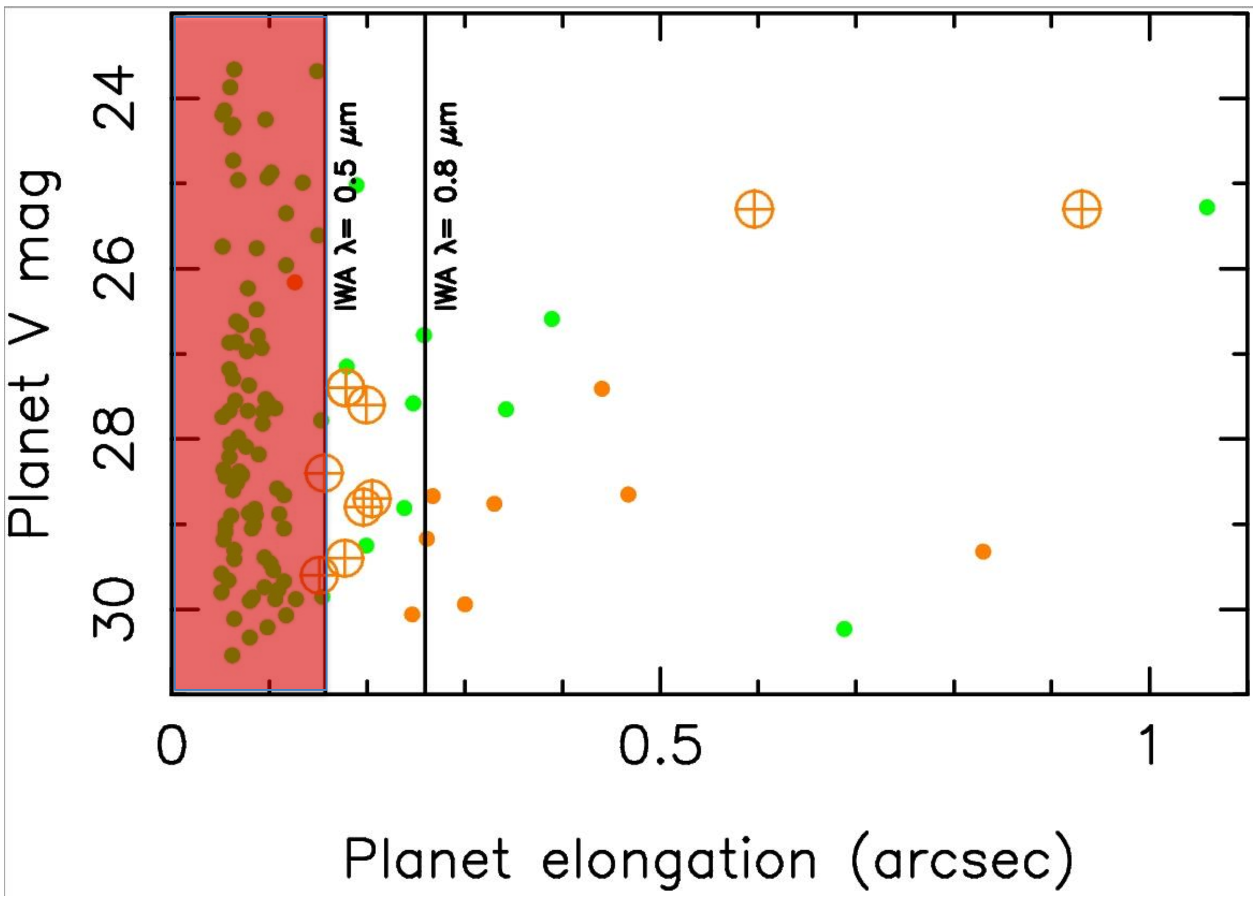
Exo-C Design Reference Mission

- **Planet characterizations: roughly 1 year of mission time**
  - Take spectra of **~20** exoplanets (both known and mission-discovered)
  - Take multi-color photometry of 20 known RV planets plus an additional **~15** mission-discovered exoplanets
- **Planet discovery surveys: roughly 1.2 years of mission time**
  - Survey **15** nearby stars for super-Earths in the HZ, 6 visits each
  - Survey **135** nearby stars for giant planets, 2-3 visits each

    Provisionally assume 10% yield, or ~15 mission-discovered planets
- **Disk imaging surveys: roughly 0.6 years of mission time**
  - Survey for habitable zone dust in **150** A-K stars
  - Deep search for disks in **60** RV planet systems
  - Resolve structure in **150** known debris disks from Spitzer/Herschel/WISE
  - Resolve structure in **40** protoplanetary disks in nearby molecular clouds

A wide range of science, containing characterizations and surveys

Exo-C Characterization of Known Exoplanets



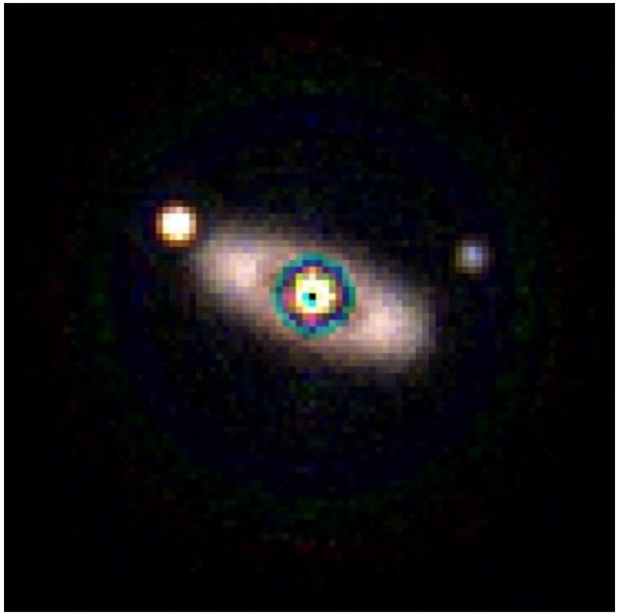
Points are known exoplanets detected by radial velocity

⊕ Earth analog as it would appear in nearby star HZ

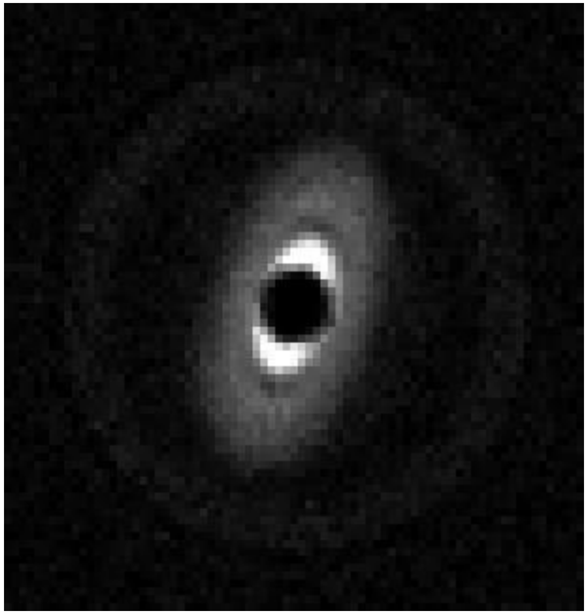
Contrast $\geq 10^{-9}$
Contrast $< 10^{-9}$

Vertical lines show 2 λ/D inner working angle for 1.4m telescope at 500 and 800 nm

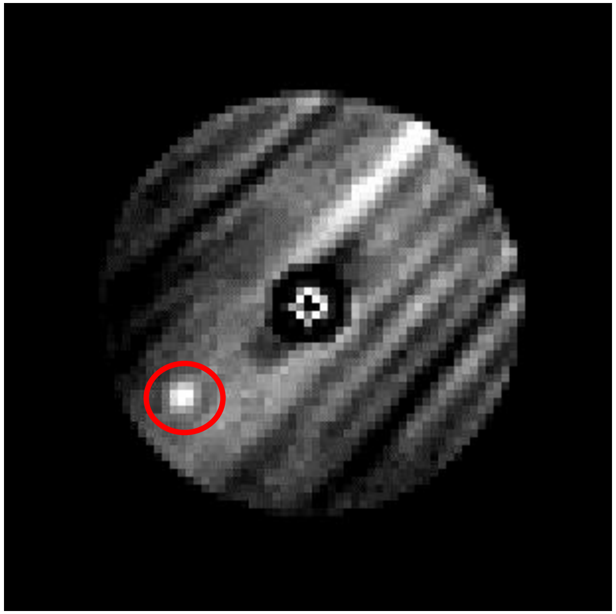
Exo-C Simulated Imagery



Altair 12 hrs each in V, R, I bands. Jupiter & Saturn analogs detected, 1 zodi dust ring from 2-4 AU



12 hr V band exposure of HIP 85790, a V= 5.6 star at 80 pc with WISE infrared excess. A 50 zodi debris disk extended to 80 AU radius is assumed.

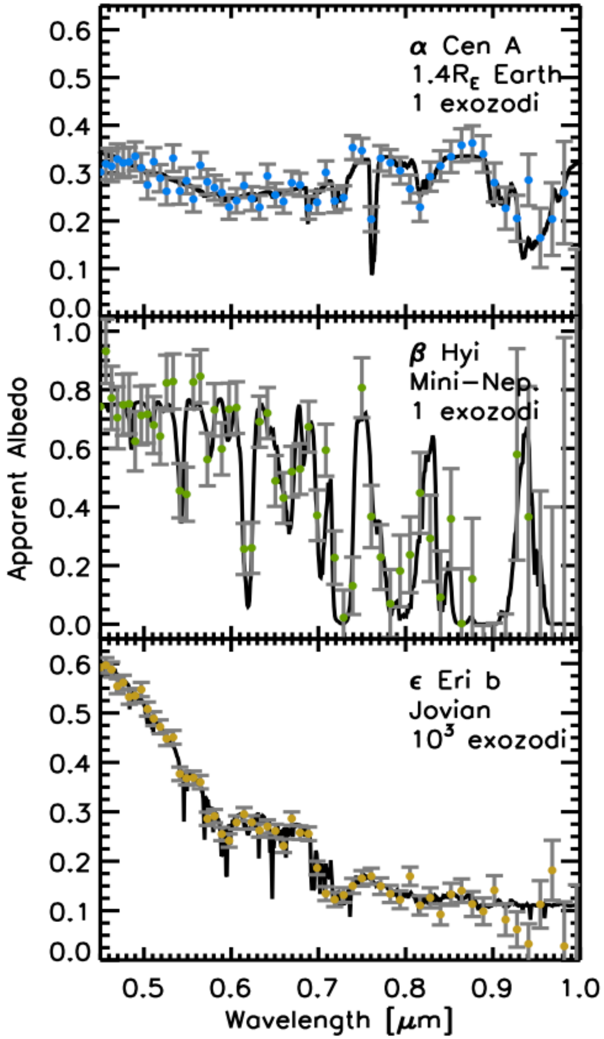


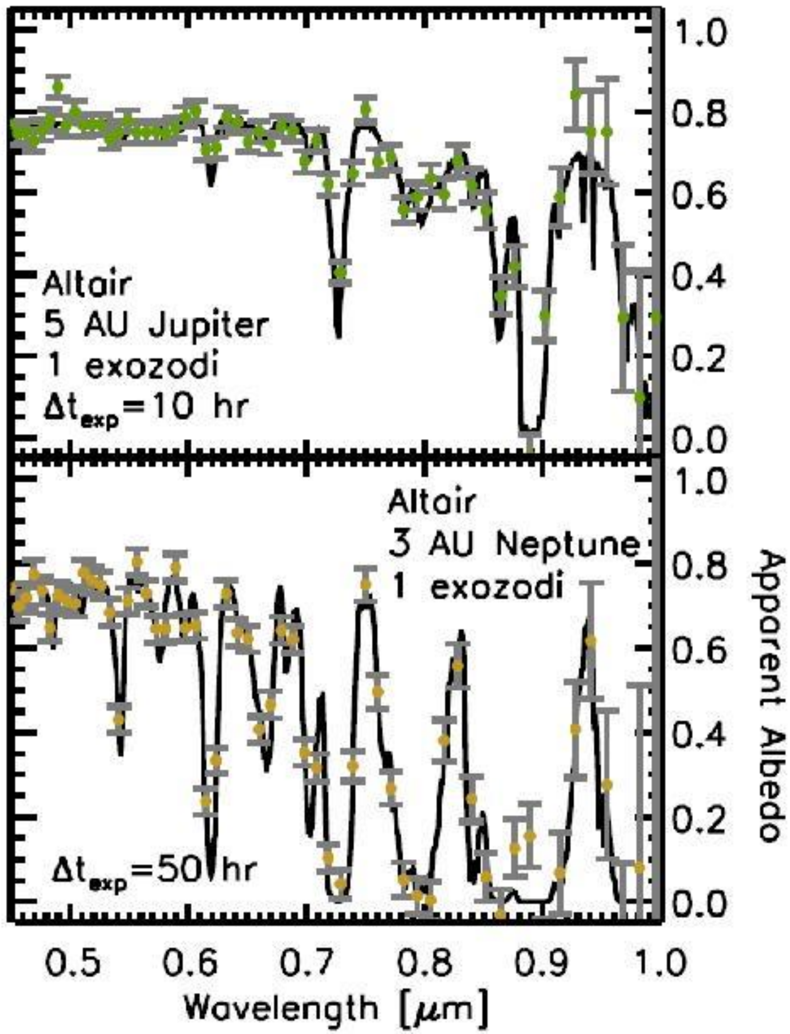
5 day V band exposure of an Earth analog in the HZ of α Cen A (occulted at center). Scattered light from α Cen B is the primary noise source; shown is a 3% residual after calibration.

All simulations use Hybrid Lyot Coronagraph optical models by John Krist

Exo-C Simulated Spectroscopy

Work by Ty Robinson (NAU)



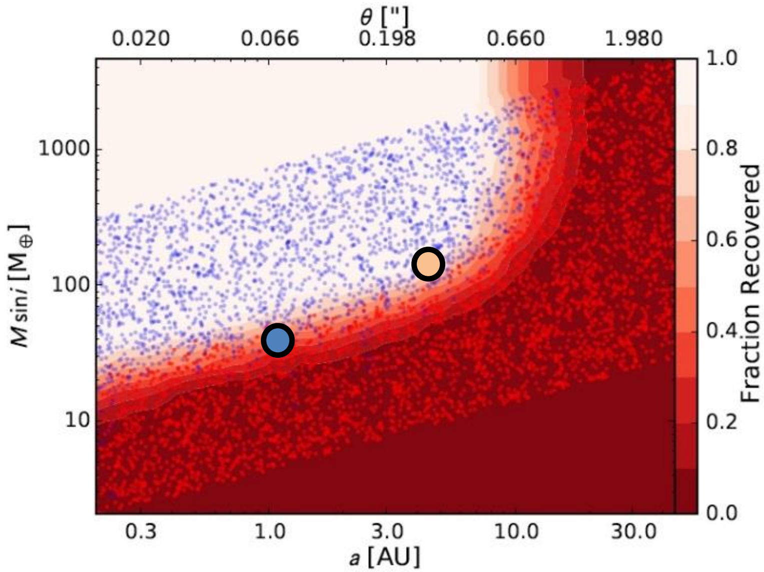


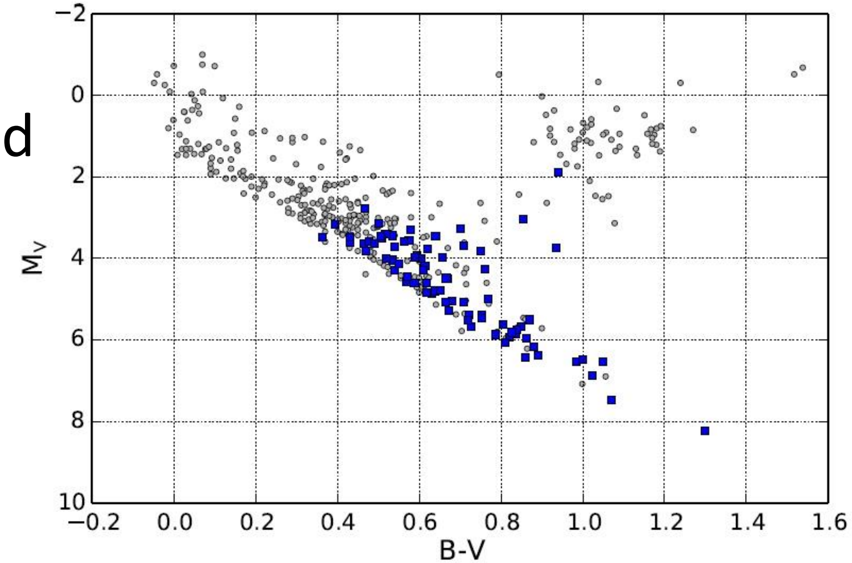
Exo-C: Discover new planets

ExEP

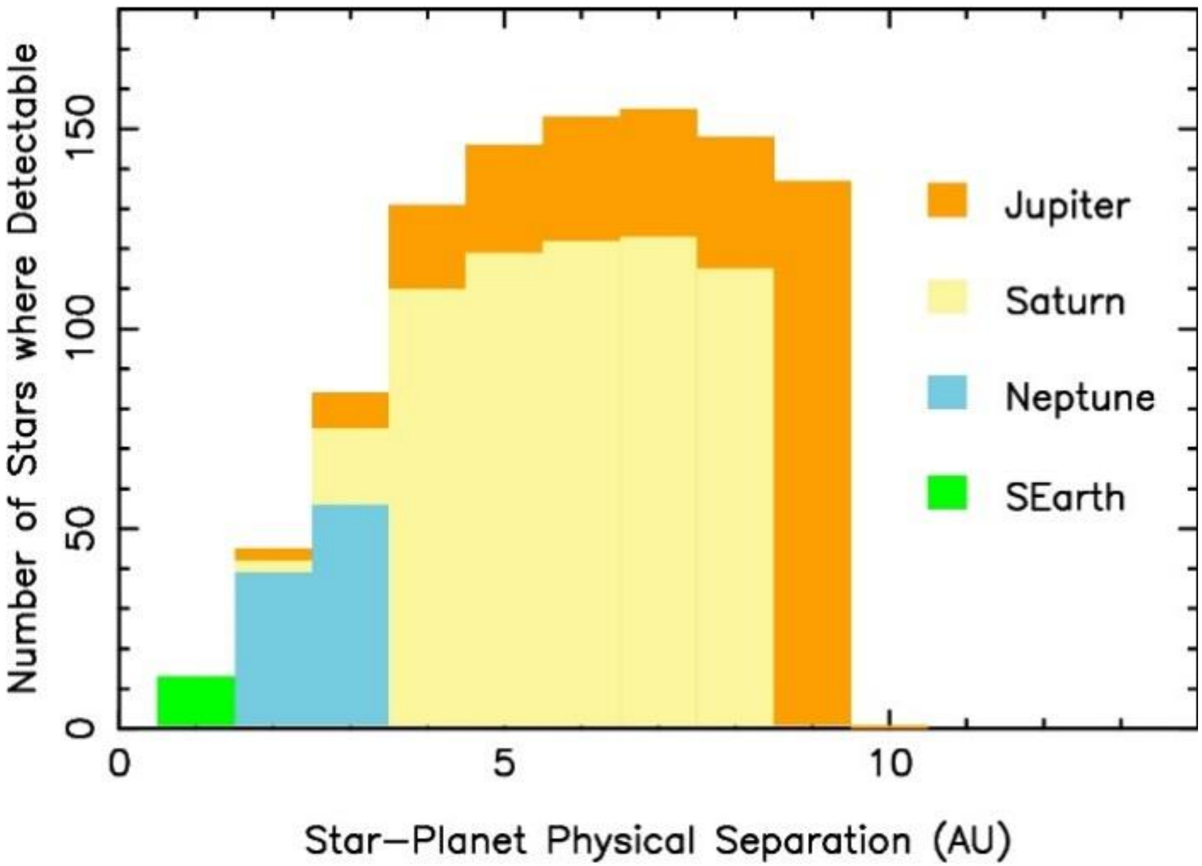
- Search for planets beyond RV limits in a nearby star sample, measure their orbits
  - Mid-F to K stars: New planets would be either small ones (such as mini Neptunes, super-Earths) unknown in our solar system, or long-period giant planets
  - A to mid-F stars: Any planets would be new. Gaia will find some of these in advance
- Right: RV coverage of WFIRST CGI and Exo-C/S targets. RV-monitored stars shown in blue. <u>2/3 of best imaging targets not accessible to RV.</u>

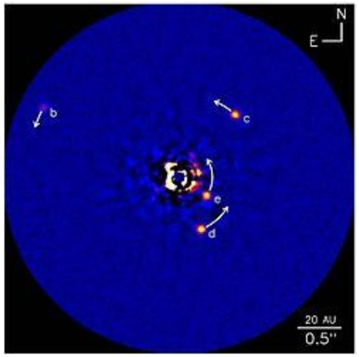
Figures from Howard & Fulton 2016





Exo-C Discovery of New Exoplanets





Histogram of detectable planets around nearby stars in total of 1 year of spacecraft time. A Search yield of ~> 15 planets is expected

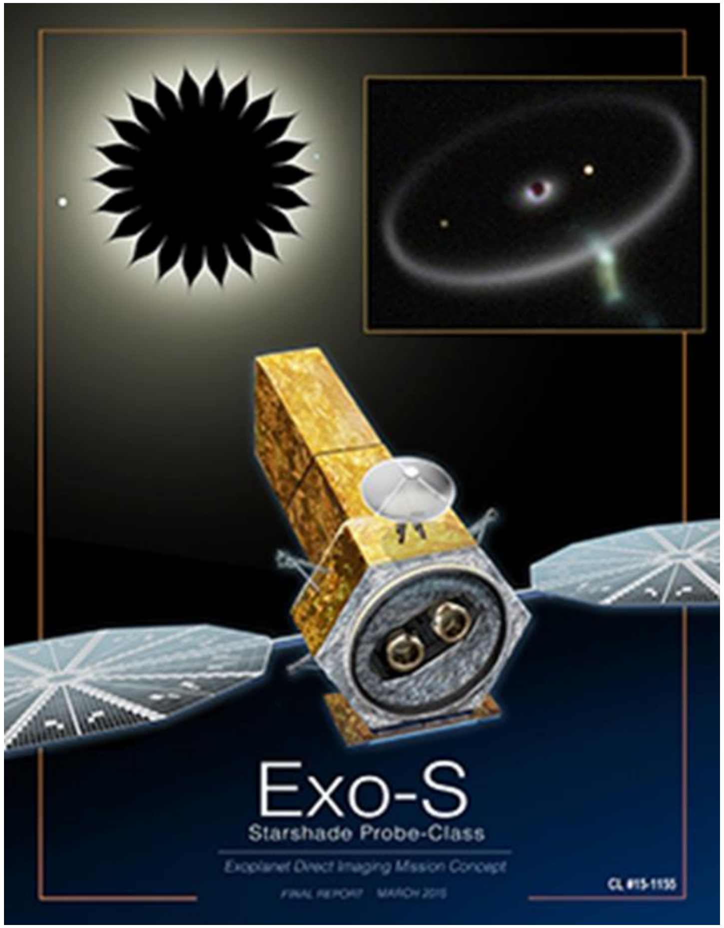
2017 Update to Exo-C Probe Study

- Prime science goals remain characterization of known giant planets & circumstellar disks, searches for exozodi & new planets beyond RV limits
- Since 2015 a few new/accessible exoplanet targets are identified by RV surveys; dozens of new debris disk targets identified in *Herschel* datasets
- WFIRST/CGI study work has improved understanding and reduced risk for the Exo-C coronagraph:
  - 40% increase in HLC system throughput relative to 2015 instrument design
  - Testbed demonstrations of Low-Order WaveFront Sensing & control and high contrast integral field spectrograph
  - Performance & qualification of low-noise EMCCD detectors
  - Higher fidelity mass and power estimates
- **Exo-C cost now $1.07 B FY 18***, a 10% increase largely due to inflation
- FY 20 start would result in FY 27 launch
- Option to fly starshade with Exo-C would require further study

Predecisional information, for planning and discussion only

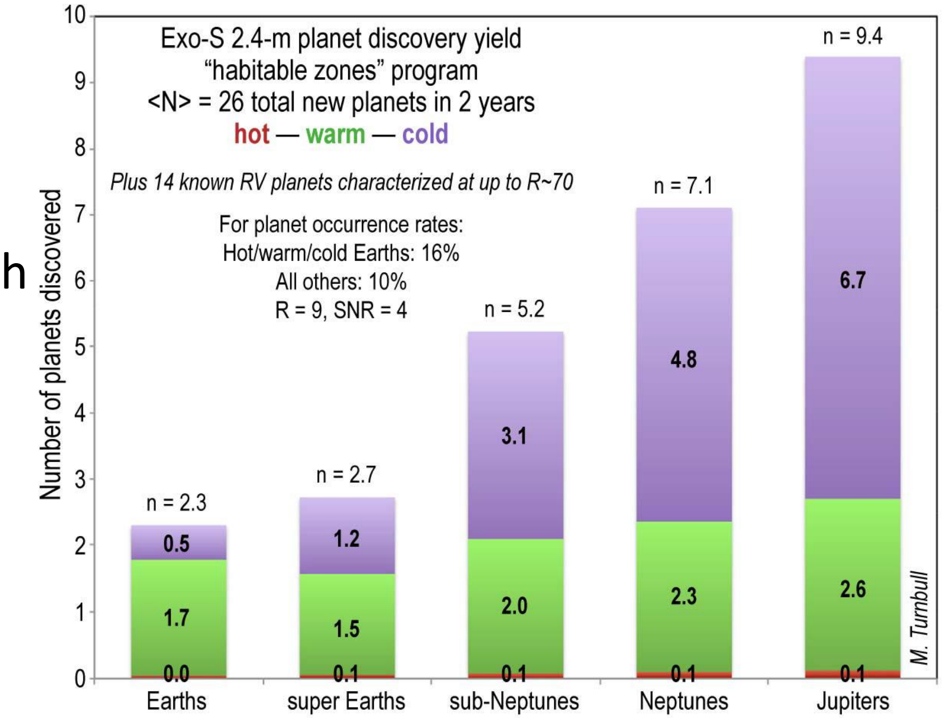
Starshade Probe Mission Options

- Seager+ 2015 studied two mission concepts utilizing a starshade for detecting & characterizing Earth analogs in a sample of ~2 dozen nearby stars. JPL strongly involved.
- There is an active 2017-2018 probe study updating that report for the 2020 decadal.
- “Rendezvous” concept would use 2.4m WFIRST telescope + CGI focal planes, is preferred option
- “Dedicated” concept includes its own 1.1 m telescope, backup plan in case WFIRST Rendezvous does not proceed



Starshade mission concept key points

- Enables smaller inner working angle, higher throughput/bandwidth than coronagraphic starlight suppression
- Opens up nearby HZs to 1-2 m class telescopes such as WFIRST, along with giant planets & disks
- Spectroscopy of exo-Earths would require finding them around the brightest targets; otherwise characterization via broad colors
- Technology is progressing since 2015 study: model validation, formation flying, allows smaller 26 m starshade
- This study report is THE crucial input to Decadal decision on WFIRST Rendezvous
- A pathfinder for larger HabEx starshade



Predicted detection yields for Rendezvous mission vs. exoplanet type (Seager+ 2015)

Starshade Rendezvous Notes

- Science yield is fuel-limited for target repositioning
- Inner working angle ~100 masis almost 2x better than Exo-C
- Seager+ 2017 study moving toward a concept of deep survey of nearest 8-10 Sun-like stars, plus a survey for exozodiacal dust
- 2 year detection survey plus third year of followup

Executive Summary of Exo-S Dedicated Mission Concept Update

- Exo-S dedicated mission is 1.1-m telescope + starshade, Earth-leading orbit
- Recent discoveries are showing richer landscape and improved modeling among smaller planets – especially “sub-Neptunes” & “super-Earths” not represented in our solar system. Exo-S can characterize temperate & cold examples of both new types among nearby stars.
- Yields updated using EXOSIMS w/new SAG13 occurrence rates:
  - ~50% increase in # of detected exoplanets, and detections of rocky planets in habitable zones increases from ~1 to 3+-2
- Smaller starshade adopted (26m vs. 30m originally)
  - Utilizes current “*S5*” tech program work; identical S5 TRL5 truss
  - Mass reduction in starshade put into added fuel for more retargets & science
  - After 2 yrs 30-m starshade has 1/2 fuel, but 26-m starshade has 2/3rd fuel remaining for follow-up observations & possible extended mission
- Tech advances allow small cost savings compared to original study
- Current cost estimate **$1.1B (FY18$)***
- Current schedule estimate: 7 $^{3/4}$ years from KDP-A (start FY23) to launch in late 2030

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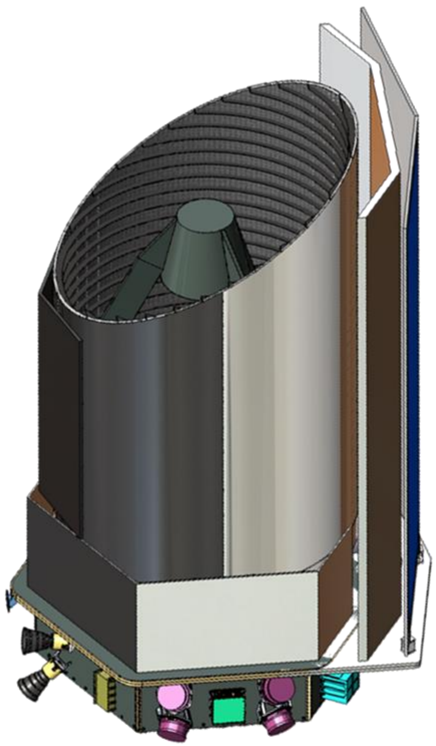
Earthfinder RV Probe Study

- EarthFinder is a space-based 1-1.4 m observatory Probe mission concept. Peter Plavchan (GMU) is PI, JPL partner
- Extremely precise and stabilized high-resolution UV-VIS-NIR spectrograph, targeting 1 cm/sec precision
- Developing scientific rationale for measuring stellar velocities of the nearest FGKM dwarf stars from space
- <u>Absence of the Earth's atmosphere improves the obtainable radial velocity precision</u>
- Unique combination of space advantages aid in mitigating stellar activity:
  - Uninterrupted wavelength coverage
  - Uninterrupted cadence
  - Diffraction-limited
  - Extreme spectral resolution



Earthfinder promise and challenge

- Imaging missions can’t determine planet mass, will require supporting measurements of stellar reflex motion
  - Planet mass determines bulk composition, and is crucial for interpreting atmospheric spectra,
- If RV (or astrometry) could identify in advance the targets with HZ planets, an imaging mission might avoid searches and save considerable observing time for other uses (exoplanet characterization, general astrophysics).
- Tradeoff between cost of the additional probe mission and the cost of search time on the large mission. But mass values are required regardless.
- Can advantages of space RV overcome the 100-1000x collecting area advantage of VLTs / ELTs ?

Conclusions

- **Studies of Direct Imaging missions with 1m class telescopes culminated in the WFIRST CGI instrument and Starshade Rendezvous option**
  - Because of the non-optimal telescope and limited observing time, WFIRST/CGI will do less science than the Exo-C mission would
  - WFIRST with a starshade would do more science than the Exo-S dedicated mission
  - Overall adding CGI and/or Starshade Rendezvous to WFIRST costs less than implementing Exo-C and/or Exo-S as separate missions. Thus the latter remain backup options.
- **Small space telescopes can do exoplanet imaging science complimentary to what upcoming ELTs will do**
  - Higher contrast capability allows access to exoplanets on wider orbits, smaller exoplanets in FGK habitable zones, and fainter levels of disk nebulosity
- **A healthy WFIRST fills the niche for this class of mission**