Exoplanet Direct Imaging: Coronagraph Probe Mission Study “Exo-C”

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Context for Study

• Flagship mission for spectroscopy of ExoEarths is a long-term priority for space astrophysics (Astro2010).

• Requires $10^{-10}$ contrast at $3 \lambda/D$ separation, (>10,000 times beyond HST performance) and large telescope > 4m aperture. Big step.

• An Internal coronagraph mission for spectroscopy of giant planets and imaging of disks requires $10^{-9}$ contrast at $3 \lambda/D$ (already demonstrated in lab) and ~1.5m telescope. Should be much more affordable, good intermediate step.

• Various PIs have proposed many versions of the latter mission 17 times since 1999; no unified approach.

• There is a similar context for a probe starshade mission.
NASA HQ Astrophysics Implementation Plan

• New strategic mission expected to start in FY 17. It will be AFTA/WFIRST if budget allows. If not, need less expensive “probe” mission options as backups. Three to choose from: WFIRST, and 2 exoplanet.

• Probe mission terms:
  • cost $1B
  • technical readiness (TRL 5) by 2017
  • Launch in 2024

• Exo-C is an 18 month HQ-funded study of an internal coronagraph probe mission
  • Science & Technology Definition Team (STDT) selected May 2013. Previous competitors now working together.
  • Engineering Design Team in place at Jet Propulsion Laboratory, July 2013
  • Interim report for March 2014, Final report due January 2015
EXO-C Key People

Science and Technology Definition Team

Karl Stapelfeldt (Chair, GSFC)
Rus Belikov (NASA/Ames)
Geoff Bryden (JPL/Caltech)
Kerri Cahoy (MIT)
Supriya Chakrabarti (UMass Lowell)
Mark Marley (NASA/Ames)
Michael McElwain (NASA/GSFC)
Vikki Meadows (U. Wash)
Gene Serabyn (JPL/Caltech)
John Trauger (JPL/Caltech)

JPL Engineering Design Team

Keith Warfield
Paul Brugarolas
Frank Dekens
Serge Dubovitsky
Bobby Effinger
Brian Hirsch
Andy Kissil

ExEP Office

Gary Blackwood
Peter Lawson

Michael Brenner
John Krist
Jared Lang
Joel Nissen
Jeff Oseas
Eric Sunada

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Approach to the Study

• Build on previous work (ACCESS, PECO, ...)
• Begin with science goals and trade studies of system-level issues: telescope design, orbit selection, pointing control, wavefront stability and control, cost
• Evaluate coronagraph options in the context of achievable system performance
• Engage Aerospace Corp. early in the study for cost feedback
• Innovate
Science Goals

• Obtain optical spectra of the nearest RV planets: measure CH$_4$, H$_2$O, Rayleigh scattering. Fix orbit inclination $\rightarrow$ planet mass.

• Search for planets beyond RV limits (Neptunes, super-Earths) in a TBD nearby star sample. Measure their orbits, carry out follow-on spectroscopy of the brightest ones
  • alpha Centauri system is a particularly important case

• Optical spectra of planets discovered by near-IR ground Adaptive Optics (AO)

• Image circumstellar disks beyond Hubble Space Telescope (HST), AO, and Atacama Large Millimeter/submillimeter Array (ALMA) limits:
  • Resolve disk structures: Size, extent, rings/gaps/asymmetries as evidence for planetary perturbations
  • Dust properties: diagnose via albedo, color, and phase function
  • Time evolution of the above from protoplanetary to debris disks
  • Assess dust content near HZ in maybe a dozen nearby sunlike stars
Accessible RV planets

Known RV planets vs. $2 \lambda/D$ @ $\lambda = 0.8 \mu m$
The family of $10^{-9}$ contrast planets

Planet size for $1\times 10^{-9}$ contrast at quadrature
alpha Cen orbit:

- 8.5” separation in 2025, growing to 10.5” a few years later

- Need coronagraph mask that covers both stars and can accommodate the variable separation
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Primary diameter</td>
<td>$\geq 1.3,\text{m}$</td>
</tr>
<tr>
<td>Uncontrolled speckle contrast</td>
<td>$1\times10^{-9}$ raw</td>
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<tr>
<td>Stability over 48 hours</td>
<td>$1\times10^{-10}$</td>
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<tr>
<td>Bandwidth</td>
<td>450-1000 nm</td>
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<tr>
<td>IWA = $2\frac{\lambda}{D}$ @ 800 nm</td>
<td>0.22 arcsec</td>
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<tr>
<td>OWA = $24\frac{\lambda}{D}$ @ 800 nm</td>
<td>2.8 arcsec</td>
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<tr>
<td>Stray light from binary companion</td>
<td>$1\times10^{-9}$ @ 8 arcsec separation</td>
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<tr>
<td>Spectral resolution $\lambda &lt; 630$ nm</td>
<td>$R &gt; 25$</td>
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<tr>
<td>Spectral resolution $\lambda &gt; 630$ nm</td>
<td>$R &gt; 50$</td>
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<tr>
<td>Astrometric precision</td>
<td>$&lt; 30$ milli-arcsec</td>
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<tr>
<td>Mission Life</td>
<td>3+ years</td>
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</table>
Engineering Trades

• Unanimous decision for unobscured telescope
  • Better throughput, resolution, stiffness, coronagraph TRL. Slightly higher cost

• Telescope aperture of 1.3-1.5m appears to be affordable

• Decided on Earth-trailing orbit
  • Better thermal stability & sky visibility than EO. No propulsion needed. Acceptable data rates.

• Integral Field Spectrograph in addition to filter imaging
  • Simultaneous measurements over $\sim$ 20% bandpass
  • Supports speckle rejection as well as planet spectra

• $\sim$900 kg payload, Kepler-like spacecraft bus, Falcon 9 launch vehicle, JPL cost estimate < $1 B
Subsystem Description

- Outer Barrel Assy
- Solar Array Assembly
- Inner Barrel Assy
- Secondary Mirror Assy
- Instrument Bench Assy
- Primary Mirror Assembly
- Primary Support Structure
- PL Avionics Assemblies
- Radiator Panel Assembly
- Star Tracker Assembly
- Isolation Assembly
- Spacecraft Assembly
  - SC Avionics Assy
  - Reaction Wheel Assy
  - Propulsion Assy
  - LV interface Ring Assy

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Instrument Layout

- Unobscured telescope form is baselined
- Cassegrain form baselined: Short Primary-Secondary spacing -> less mass
- Deformable Mirror (DM) 48x48 elements
- Lateral Instrument Configuration along side Inner Barrel Assembly
Current Work

• Initial Thermal Performance Modeling
• Initial Structural Modeling for configuration and loads
• Pointing Requirements Generation
• Back end Instrument optical layout including FGS, LOWFS, science camera, and IFS
• Coronagraph trade in progress
Choosing a coronagraph

• Pre-requisite is having some understanding of likely pointing performance, thermal stability, and control authority over time-variable low order aberrations.

• Six concepts being evaluated: hybrid Lyot, PIAA, shaped pupils, vector vortex, two visible nuller variants.

• Optical simulations flow to science yield estimates. Telescope pointing stability strongly affects science yield. Demonstrated lab performance will be highly weighted.

• EXO-C decision will be totally independent of AFTA choice
# Thoughts on 3 year Design Reference Mission

## Table

<table>
<thead>
<tr>
<th>Science Type</th>
<th>N_target</th>
<th>N_visit</th>
<th>t_I</th>
<th>T_Obs</th>
<th>T_NO = T_SC + T_T + T_IO</th>
<th>Total Mission Time</th>
<th>Total Observation Efficiency of each Science Type</th>
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<tbody>
<tr>
<td>Spectroscopy of Known Exoplanets (known from RV and exo-C survey)</td>
<td>30</td>
<td>1</td>
<td>100</td>
<td>125</td>
<td>8</td>
<td>135</td>
<td>93%</td>
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<td>Planet discovery surveys</td>
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<td>Survey nearby stars for super-Earths within the habitable zone</td>
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<td>6</td>
<td>20</td>
<td>100</td>
<td>8</td>
<td>140</td>
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<td>Search for giant planets around nearby stars</td>
<td>150</td>
<td>3</td>
<td>20</td>
<td>375</td>
<td>8</td>
<td>525</td>
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<td>Disk Imaging Surveys</td>
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<td>Detection survey in RV planet systems</td>
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<td>1</td>
<td>12</td>
<td>100</td>
<td>3</td>
<td>125</td>
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<td>Known debris disks within 40 pc</td>
<td>80</td>
<td>1</td>
<td>6</td>
<td>20</td>
<td>3</td>
<td>30</td>
<td>67%</td>
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<td>Young debris disks from WISE</td>
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<td>1</td>
<td>6</td>
<td>30</td>
<td>3</td>
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<td>Nearby protoplanetary disks</td>
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<td>1</td>
<td>6</td>
<td>20</td>
<td>3</td>
<td>30</td>
<td>67%</td>
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<td>Total on-orbit ops time</td>
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<td>Initial On-Orbit Checkout (days)</td>
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<td>Total (days)</td>
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<td>1090</td>
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<tr>
<td>Total (years)</td>
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</table>
General Astrophysics Capability

- High contrast science on post-main sequence stars, AGN/quasars, ...
- Imaging camera will have 1 arcmin FOV with small filter set; IFS will have ~2.8” FOV.
- Camera and IFS useable without coronagaphic spots
- Pointing performance for targets other than bright stars is still TBD. Support for moving targets doable but not in baseline cost.
- Not currently planning for UV capability (cost)
- A second instrument could be accommodated in terms of payload mass/volume, but not in terms of cost.
Conclusions

• Exo-C Study is well underway. We will show what an affordable, optimal, high TRL exoplanet imaging mission can do.

• We are eager to get our first Structural-Thermal-OPTical models to assess telescope stability

• Capability to search alpha Cen system may be key to selling the mission

• Please see me here, or send me your suggestions for things we should look into or how you’d like to help: karl.r.stapelfeldt@nasa.gov.