

- 259.05. High Contrast Science Program for the Exo-C Space Telescope Mission <u>Karl R. Stapelfeldt et al.</u>
- 259.06. Exo-C: Mission and Science Payload Design <u>Frank G. Dekens et al.</u>
- **259.07.** Enabling Technologies for Characterizing Exoplanet Systems with Exo-C *Kerri L. Cahoy et al.*

Why a dedicated coronagraph probe mission ?

 RV and transit surveys have shown exoplanets are abundant. Spectral characterization is the natural next step; reflected light planets are unique targets.



Atmosphere features are more readily detected by imaging than by transits

GJ 1214b model spectra by Caroline Morley and Mark Marley

- RV and transit surveys have shown exoplanets are abundant. Spectral characterization is the natural next step; reflected light planets are unique targets.
- A ~1.4m aperture can be very effective if coronagraph requirements can drive the mission design
- Community interest in this mission class shown by at least 13 proposals submitted to Mid-Ex, Discovery, Astro 2010 ASMCS, and ESA M class since 1998
- Agility of internal coronagraph allows large number of targets to be observed and at multiple epochs
- Natural technology step to ExoEarth flagship mission
- Kepler proved stable 1.4m observatory costs < \$1B

ExEF

Exoplanet Science in 2024

- Indirect detections: RV surveys have detected 10 yr period planets
 ≥ Saturn mass, 1 yr period planets ≥ Neptune mass around stars F8
 & later. GAIA detects short-period Jupiters. Target lists for spectra.
- <u>Transits</u>: TESS has extended Kepler results to brighter stars, defining planet mass-radius relationship. JWST+ELTs get transmission spectra for some of these. PLATO mission begins. All these provide target lists for outer planet imaging searches
- <u>Exoplanet Direct Imaging</u>: Ground AO has obtained spectra of dozens of young/massive planets in near-IR thermal emission. Likely contrast limit of ~10⁻⁸ set by atmospheric turbulence. JWST may image cold/wide giant planets around M stars (contrast ~10⁻⁶).
- <u>Disk Imaging</u>: ALMA has redefined knowledge of protoplanetary disks, but cannot map tenuous debris disks at subarcsec resolution.
 Ground AO imaging polarimetry of brighter disks.

Science Opportunities for Exo-C

- Obtain optical spectra of nearest RV planets: Measure gas absorbers, fix planet mass.
- Search for planets beyond RV limits (Neptunes, super-Earths) in a nearby star sample. Measure orbits, do spectroscopy of the brightest ones
 - alpha Centauri system is a very important case
- Image circumstellar disks beyond HST, AO, and ALMA limits
 - Resolve structures driven by planetary perturbations, including dust in nearest habitable zones
 - Time evolution of disk structure & dust properties from protoplanetary to debris disks
- Probe a few systems for exo-Earths, if telescope stability and exozodi are favorable









Telescope primary mirror	1.4 m diameter
Uncontrolled speckle contrast	1e-09 raw at IWA, better further out
Contrast stability	1e-11 two hours after slew or roll
Spectral coverage	450–1000 nm
Spectral resolution λ > 500 nm	R = 70
Inner Working Angle 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	3e-8 raw @ 8", TBD additional
companion	reduction from wavefront control
Astrometric precision	< 30 milliarcsec
Fields of view	42" imager, 2.2" spectrograph
Mission lifetime	3 years

NASA

Known exoplanets accessible to 1.4m







Exo-C Planet Search Space



Using Hybrid Lyot Coronagraph & V band filter 5 days maximum integration and 0.75 years total search time

Exo-C imaging will detect & resolve structure in a large number of Debris

Predicted disk sizes & contrasts for Herschel disks d< 40 pc

<u>Red points:</u> The small number of disks imaged to date in scattered light

Black points: Disks with sizes known from Herschel data (measured at 5" resolution)

<u>Hollow points</u>: Disks whose sizes can only be estimated from far-IR SED & assumed Dust properties



ExoPAG 11

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3.0

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 all the above 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 150 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 160 known debris disks from Spitzer/Herschel/WISE
 - Resolve structure in **80** protoplanetary disks in nearby molecular clouds

A wide range of science, containing characterizations and surveys



Simulated Imaging Results



6 hr V band exposure of Altair: 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. Beat pattern in the streaks is a simulation artifact.

All images use Hybrid Lyot Coronagraph optical models by John Krist

Simulated Spectroscopy Results



General Astrophysics Capability ?

- Exo-C's small fields of view (42 arcsec for imager; 2.2" for imaging spectrograph) will limit general astro applications
- Coronagraph needs stars with V < 13 for pointing system to operate as currently designed
- High contrast science applications for post-main sequence stars and AGN/quasars; see Dennis Ebbets' talk to follow
- Use of camera and IFS without coronagraphic spots, or on targets with V≥ 13, would require pointing system redesign
- A second instrument could be accommodated in terms of payload mass/volume, but not within \$1B cost cap.
 - Optical/near-IR photometer/spectrometer for transit work can likely be accommodated on instrument bench

ExFP



- Earth-trailing orbit as for Kepler
 - Good thermal stability & sky visibility, no propulsion needed
- Unobscured 1.4m Cassegrain telescope
 - Better throughput, spatial resolution, stiffness, coronagraph technical readiness vs. obscured
- Hybrid Lyot coronagraph for 2017 project start; Vector Vortex and PIAA still under consideration for later start
- Active thermal control of telescope & instrument
- Bright science target star is reference for precision pointing and for following low-order wavefront drifts
- ~1000 kg observatory mass, Kepler-like spacecraft bus, Falcon 9 class launch vehicle



Exo-C Design Evolution during 2014



- Reduced telescope aperture from 1.5m to 1.4m (cost ↓)
- Solar array expanded into a sunshield for entire telescope (improves wavefront stability)
- Replaced outer barrel with thermal blankets (mass ↓)
- Lowered stack height (mass ↓)
- Electronics boxes moved inside spacecraft bus (thermal stability)
- Fine pointing requirement relaxed to 0.8 mas (margin +)
- Increased stray light baffling
- Two-layer instrument bench



Final Design

<u>Interim Design</u>

Subsystem Description



ExoPlanet Exploration Program



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Pointing Control System

A robust pointing architecture that leverages flight proven technologies.

Pointing Requirements				
Telescope Pointing (Angle in the sky, RMS per axis)				
2 milliarcsec (Line-of-sight tip/tilt)				
10 arcsec (Line-of-sight roll)				
16 milliarcsec (Line-of-sight tip/tilt)				
10 arcsec (Line-of-sight roll)				
Coronagraph Pointing (Angle in the sky, RMS per axis):				
0.2 milliarcsec (Line-of-sight tip/tilt)				
0.8 milliarcsec (Line-of-sight tip/tilt)				

Key Features of the Pointing System	Exo-C	IRIS SmEx (2013)	PICTURE Sounding Rocket (2011)	Kepler Discovery (2009)	Spitzer (2003)	Chandra (1999)	Hubble (1990)	TRACE SmEx (1990)
Fine-guidance sensor (FGS)	Х	Х	Х	Х	Х	Х	Х	Х
High-bandwidth fast-steering mirror (FSM)	Х	X	Х					Х
Enhanced attitude control system (ACS) using FGS	Х	Х		Х		Х	Х	Х
Passive isolation	Х					Х	Х	
Low-disturbance Earth-trailing orbit	Х			Х	Х			
High-stiffness observatory (no deployables/articulations)	Х			Х	Х			
In-flight pointing stability performance		ACS:	ACS:	ACS:	ACS:	ACS: 250	ACS:	ACS:
(RMŠ)		250 mas	600 mas	25 mas (<5	40 mas	mas	5 mas	5 mas
		Instrument:	Instrument: 5	Hz)				Instrument:
		50 mas	mas	3 mas (<0.0001 Hz)				100 mas

Choosing a coronagraph

- Five architectures were evaluated: Hybrid Lyot, PIAA, shaped pupil, vector vortex, and the visible nuller
- Realistic optical system models for each with wavefront control and telescope pointing errors
- Contrast maps and individual throughputs used to predict science yield for each. Three met science requirements and have path to readiness, participated in second design cycle
- Summary evaluations result in <u>Hybrid Lyot as baseline</u> for a 2017 project start. Vector Vortex and PIAA remain options for a later start.



Structural Thermal Optical Performance

Image contrast evolution after telescope moves





- Model predictions suggest Exo-C final design will have ~2 hr settling timescale and very small contrast drifts
- This would allow low overheads and routine use of two-roll observing strategy



Technology Readyness

- Exo-C technology is built on years of TPF & TDEM investments and is closely aligned with planned AFTA coronagraph investments and demonstrations.
- Exo-C bandwidth & contrast requirements already met by Hybrid Lyot coronagraph at 3 λ/D inner working angle. 2 λ/D inner working angle requirement met by PIAA & Vector Vortex coronagraphs, but at 10⁻⁸ contrast and 10% bandwidth.
- Need to demonstrate all the above in a single instrument in the presence of dynamic pointing & wavefront errors → Low-order wavefront control. JPL High Contrast Imaging Testbed

48x48 Xinetics deformable mirror has been shake tested







Summary

- Exo-C uses an internal coronagraph with precision wavefront control to conduct high contrast imaging at visible wavelengths
- Exo-C's science goals are to:
 - Spectrally characterize at least a dozen RV planets
 - Search >100 nearby stars at multiple epochs for planets down to $\sim 3 \times 10^{-10}$ contrast. Characterize mini-Neptunes, search the α Centauri system.
 - Image hundreds of circumstellar disks
- During 2014 Exo-C's final design evolved significantly to improve performance and reduce cost & risk.
- The second design iteration was costed by Aerospace Corp. at \$ 1.1 B. Our third iteration was submitted in December and is expected to come in at lower cost.



ExEP

Exo-C Study



Conclusions

- Exo-C's aperture, orbit, spacecraft, & lifetime are virtually the same as those of the Kepler mission, which at \$700 M is our cost reference.
- Exo-C's estimated costs are significantly less than those of similar coronagraph mission concepts evaluated by Aerospace for Astro 2010
- The Exo-C design effort demonstrates that a compelling science mission can be done at the mandated Probe mission cost cap of \$1 B.
- Final report writing/editing continues during January for submission to NASA HQ at the end of the month and presentation to the CAA at end of March.





National Aeronautics and Space Administration

www.nasa.gov

http://exep.jpl.nasa.gov/stdt/exoc/



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Exoplanet Probes Linkage to Astro 2010



"The (EOS) panel did evaluate, and found appealing, several "probe-class" concepts employing ~1.5-m primary mirrors and internal star-light suppression systems, often coronagraphs with advanced wavefront control. Each was judged to be technically feasible after completion of a several year technology development program, and could cost significantly less than a precision astrometry mission like SIM Lite. Such a mission could image about a dozen known (RV) giant planets and search hundreds of other nearby stars for giant planets. Importantly, it could also measure the distribution and amount of exozodiacal disk emission to levels below that in our own solar system (1 zodi) and detect super-Earth planets in the habitable zones of up to two dozen nearby stars. These would be extremely important steps, both technically and scientifically, toward a mission that could find and characterize an Earth-twin."

Science frontier discovery areas:

Identification and characterization of nearby habitable exoplanets How diverse are planetary systems ? How do circumstellar disks evolve and form planetary systems ?

"... a critical element of the committee's exoplanet strategy is to continue to build the inventory of planetary systems around specific nearby stars"



α Centauri Orbit sets stray light requirement



8.5" separation in 2025, increasing to 10.5" in 2028.
<u>STEPS FOR CONTROL OF</u>
<u>SPILLOVER LIGHT:</u>

- Coronagraph mask
 concepts to block both
 stars and accommodate
 the variable separation
- Primary mirror surface quality specifications at 100 cycles/aperture
- Agile dark hole using deformable mirrors
- Careful baffling and control of internal reflections

Accessible RV Planets vs. Aperture Size



NASA

Mission Observing Time Allocations



	Visits		Science Observation times			
	N_target	N_visit	T_integ	T_Obs	T_M	Efficiency
			(hrs)	(days)	(days)	
Planet characterizations						
Spectroscopy of Known Exoplanets (known from RV and exo-C survey)	20	1	250	208	215	97%
Multi color photometry of Known Exoplanets (known from RV and exo-C survey)	35	1	80	117	128	91%
Planet discovery surveys						
Survey nearby stars for super-Earths within the habitable zone	15	6	25	94	113	83%
Search for giant planets around nearby stars	150	2.3	20	288	359	80%
Disk Imaging Surveys						
Survey for HZ dust in A-K stars	150	1	8	50	69	73%
Detection survey in RV planet systems	60	1	12	30	38	80%
Known debris disks within 40 pc	60	1	12	30	36	83%
Young debris disks from WISE	100	1	12	50	60	83%
Nearby protoplanetary disks	80	1	6	20	28	71%
Total on-orbit ops time (days)				886	1046	
Initial On-Orbit Checkout (days)					60	
Total (days)					1106	80%
Total (years)					3.0	

Exo-C Design Trades



Trade	Outcome
Telescope obscured vs. non-obscured	Unobscured aka "off-axis"
Telescope design	Cassegrain
Telescope material: Glass vs. silicon carbide (SiC)	Low CTE glass
Orbit	Earth-training
Aperture size	1.4 m
High-gain antenna (HGA)	Fixed
Isolators: between reaction wheel assembly (RWA) and spacecraft, and again between spacecraft and payload	Two passive layers
Deformable mirrors	Two 48 × 48 devices for 2017, investigate larger formats for later launch
Instrument configuration: Lateral vs. behind primary mirror	Lateral
Mission design	Baseline configuration in §6
Low-order wavefront sensor (LOWFS) design	Zernike WFS, spectral splitting
Spacecraft bus	Kepler type
Solar array configuration	Fixed
Field of regard	Boresight angles of 45-135 degrees w.r.t. the Sun
Mission lifetime	3 years, consumables for 5 years
Pointing architecture	Isolation, flight management system (FMS), payload, and spacecraft interface
Spectrometer architecture	Integrated field spectrometer (IFS): 76x76 lenslet array, R= 70
Telescope stability—thermal architecture	Multizone heater control of telescope barrel and primary mirror; sunshade for telescope
Secondary mirror configuration	Actuated secondary
Telescope metering structure configuration	Integrated with barrel assembly
Instrument architecture	Coronagraph, imaging camera, IFS, fine-guidance sensor (FGS)
Coronagraph architecture	Hybrid Lyot baseline for 2017, Vector Vortex and PIAA still considered for later launch
Science detectors	Science camera and IFS both use 1K x 1K EMCCD for 2017, 2K x 2K for later launch

Pointing System Block Diagram



NASA

NASA

STDT-Coronagraph Top Level

(Preliminary Schedule)



Probe studies are directed to be based on a Phase A start at the beginning of FY17, project PDR in FY19 and a launch no later than 12/31/2024. The schedules includes funded schedule reserves per JPL Design Principles.