



Hybrid Observatory for Earthlike Exoplanets: Conceptual Breakthrough

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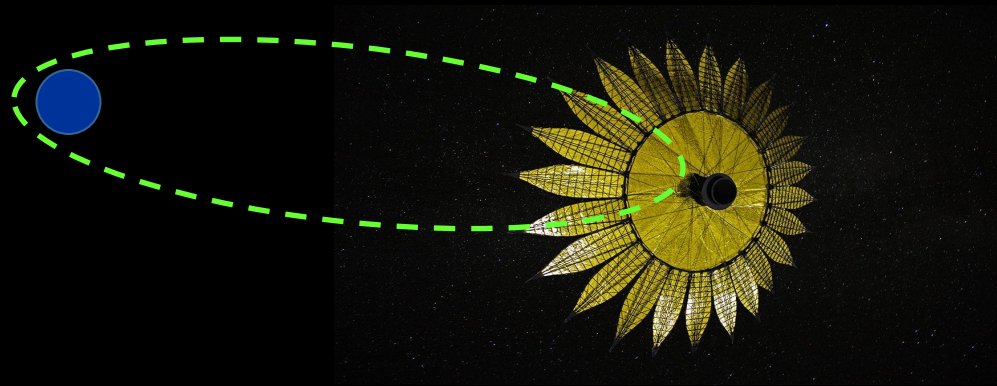
With thanks to Webster Cash and NIAC (2005-2008) who got starshades going

<https://www.colorado.edu/aps/webster-cash>

Cash, W., "Detection of Earth-like planets around other stars using petal-shaped occulter", *Nature*, 442, 51-53, (2006)

With 100 m orbiting starshade, see and get spectra for maximum number of solar systems

24-39 m Extremely Large Telescope (ELT) with visible AO (adaptive optics) on Earth



>170,000 km altitude matches observatory $v \sim 400$ m/s
Laser beacon at center enables adaptive optics
Jets/ hot gas keep alignment
Solar electric propulsion for next target orbit

Solar System at 5 pc in 1 minute

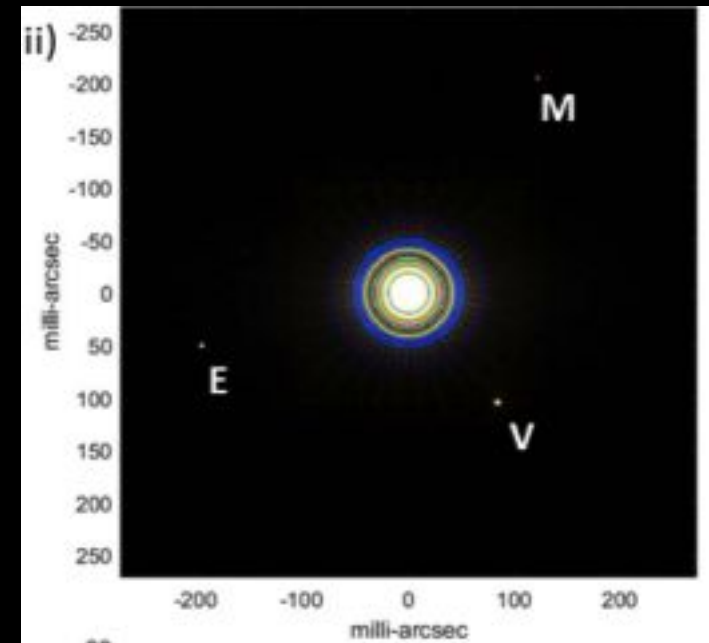


Image by Shaklan

Extraordinary Scientific Power

- Maximum sensitivity
 - Diffraction and background limited speed proportional to $(D/d)^4/B$ (D = telescope diameter, d =star distance, B = background)
 - Maximum target distance, number of candidate systems
 - Small planets, dwarf planets, comets, dust clumps
 - Brightness changes with time (planet rotation, weather, continents?)
- Maximum contrast against exo-zodi dust clouds, $\sim D^2$, planet brighter than background
- Excellent contrast (rejection of starlight), $> 10^{11}$ (sun is 10^{10} x as bright as Earth)
- Maximum angular resolution: 3 milliarcsec ($1.22 \lambda/D$) at 500 nm
 - no doubt, no confusion,
 - clear separation of planets from starshade and each other
- Planet orbit motion detectable in 5 days
- Water and oxygen in exo-modern-Earth measurable despite telluric bands

Water, Oxygen, Ozone, and Vegetation Red Edge of Earthshine

Ozone

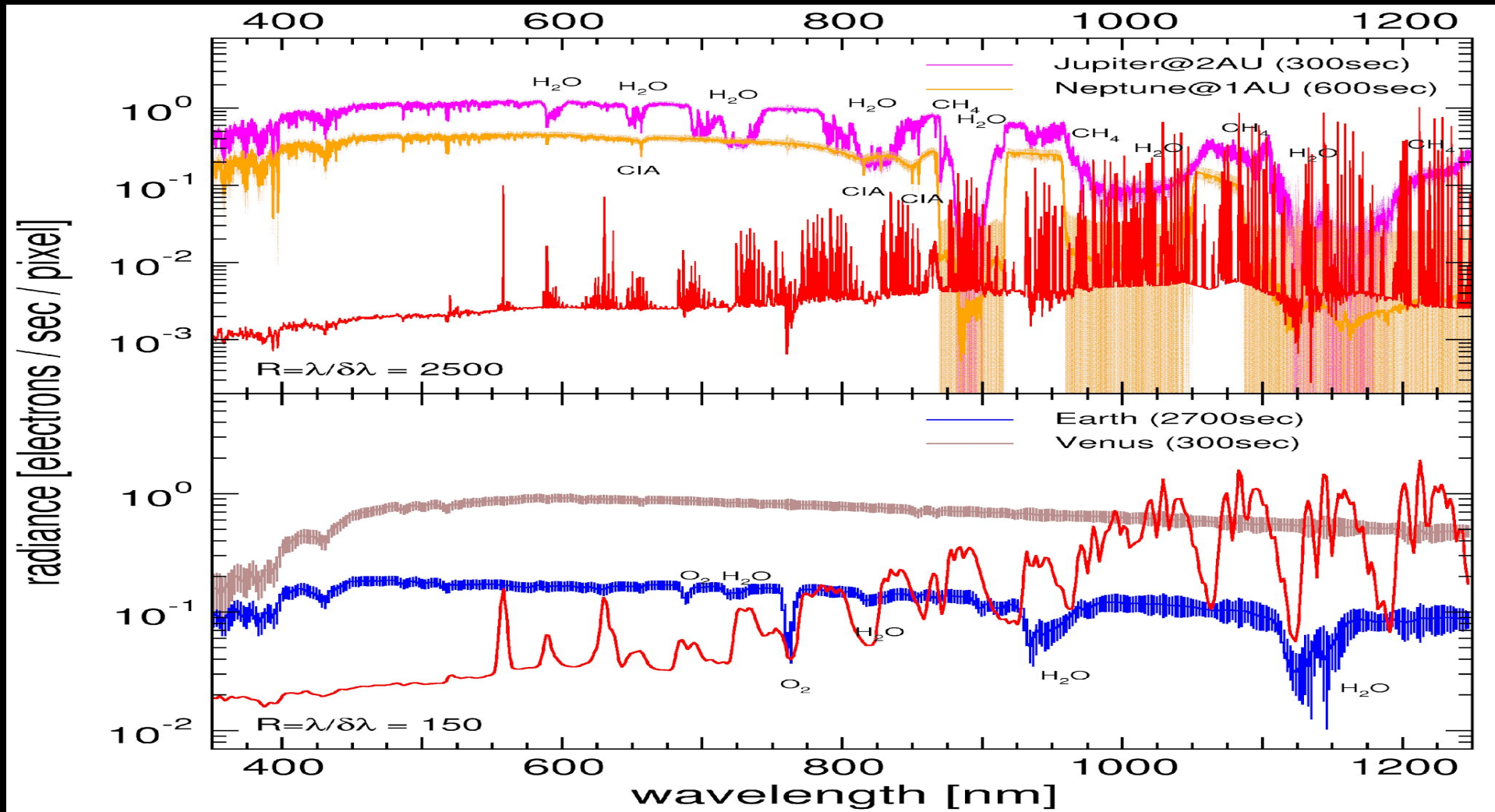
Ozone

Water

Oxygen

Vegetation

HOEE observes atmospheric spectra with oxygen and water



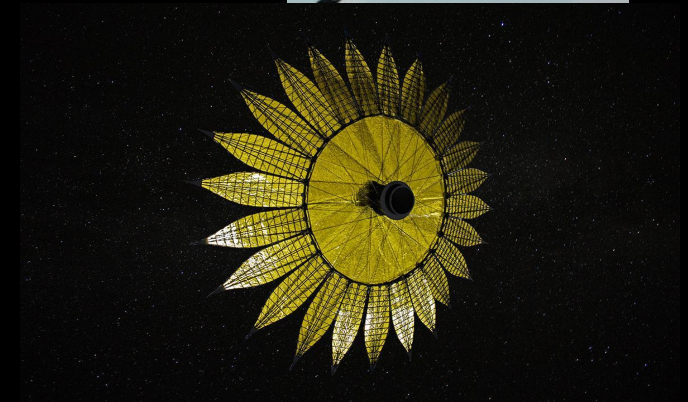
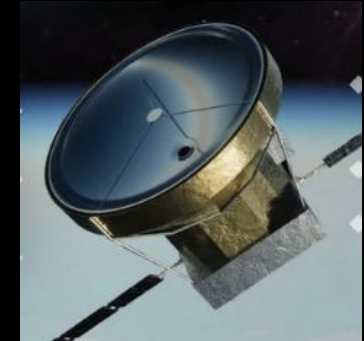
Water and oxygen in an Earth-like planet (blue curve) 5pc (16 light years) away in 1 hour. Corrected for telluric absorption. Lower red curve is sky background, fainter than the planets. Venus in gray. Warm Jupiter in purple, warm Neptune in yellow.

HOEE Advantages

- Programmatic
 - Telescope under construction, European money
 - Starshade constructible with ordinary space engineering
 - First opportunity to see Earth 2.0
- Scientific
 - Huge increase (minutes versus days) in observing speed and target distance:
 - $(D/d)^4/B$, where D = diameter, d = target distance, B = background including exozodi light
 - Distinguish exozodi structures if any
 - Monitor brightness variation in hours
 - Find fainter, smaller planets
 - Unambiguous detection: sharp images, far from star
 - Potential access to ozone in UV, if AO improves

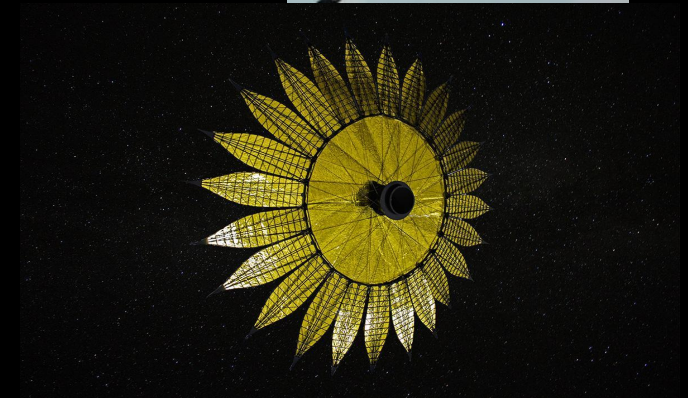
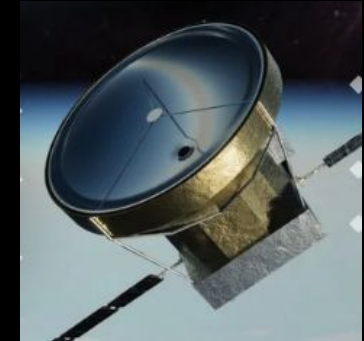
Hybrid Possibilities

- Photometric calibration, NIST standards:
- Landolt mission approved (P. Plavchan), CANDLE study (S Deustua)
- Adaptive optics for direct imaging and spectroscopy of exoplanets: Orbiting Configurable Artificial Star (ORCAS); will be proposed by S. Seager (MIT) et al
- Adaptive optics for solar corona with DKIST
- Adaptive optics for imaging interferometers (visible)
- Adaptive optics for ALMA (mm) and meter-wave?
- Polarization standards (radio, mm)
- Black Hole Explorer (BHEX): will be proposed by M. Johnson (CfA) et al
- HOEE (Hybrid Observatory for Earthlike Exoplanets) (Mather et al., NIAC)
- Other space VLBI



Orbit Classes

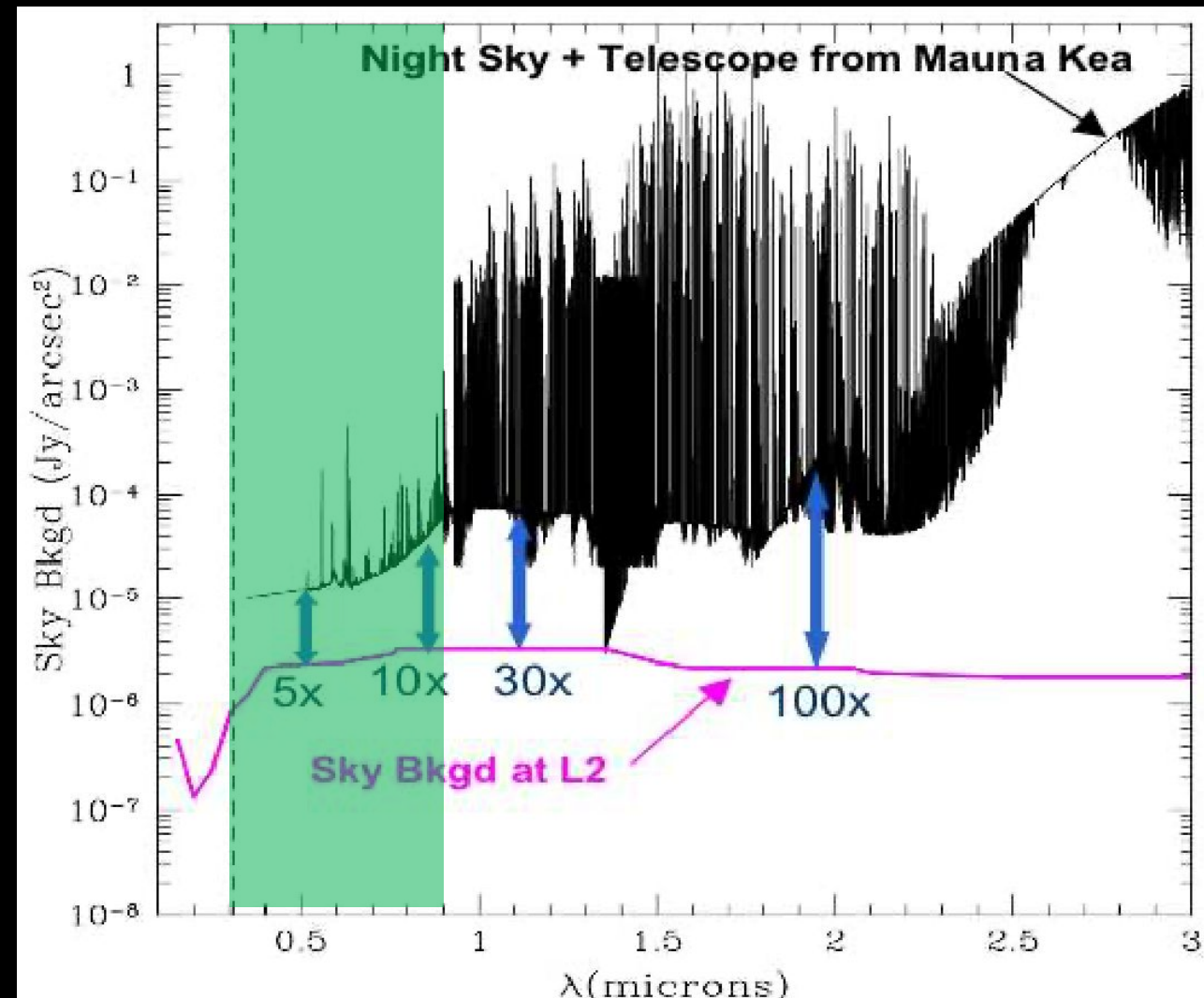
- Low Earth Orbit: fast (8 km/s), precesses, 500 km
- Polar Sun-Synch: $h \sim 1000$ km. Plane precesses to match Sun.
- HEO: sweeps around sky, good for VLBI, $\sim 10,000$ km (particle hazards)
- GEO, 36,000 km, sweeps a circle every day, 15 arcsec/sec
- Near Astrostationary: long ellipse. Hovers near target within arcseconds, for hours, at $> 170,000$ km, can repeat every $N \sim 5$ days
- Active astrostationary: propulsion maintains alignment to target star
- L1 heliostationary: 1.5 Mkm. Fixed on Earth-Sun line. Projected position sweeps 0.5° ellipse across the Sun every day



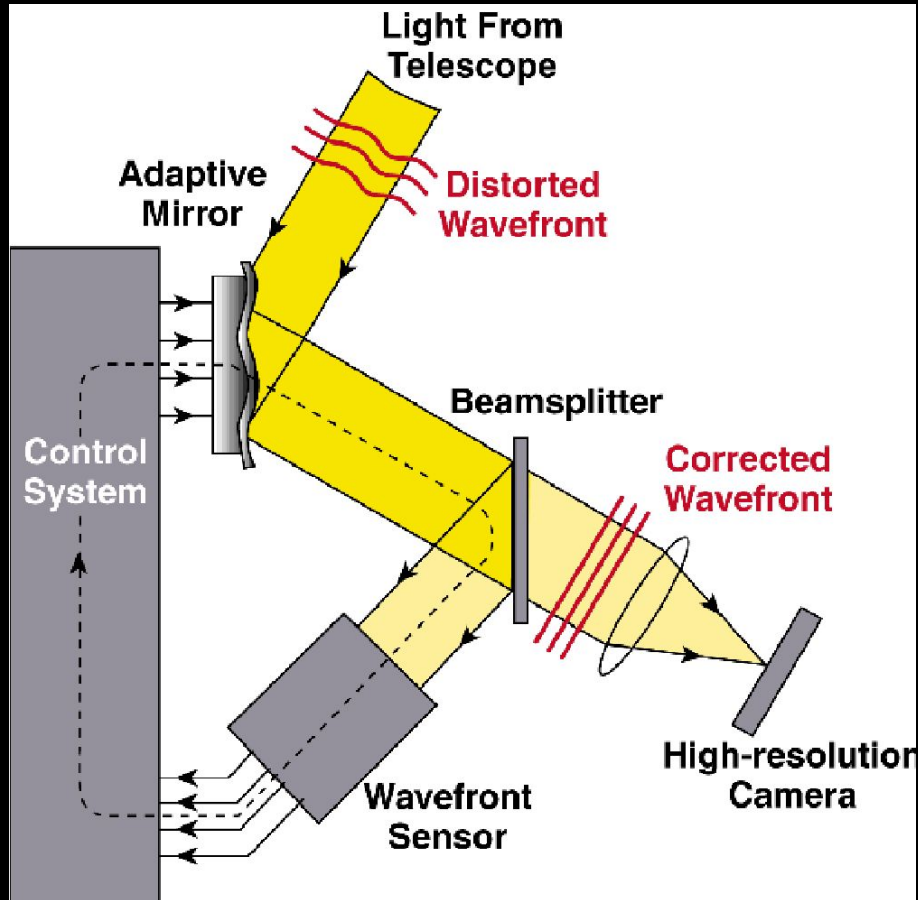
Visible band AO beats feasible space telescopes

- For sky background & diffraction limited telescope, point source observing speed proportional to D^4/B where, D is diameter, B is background
- AO reduces pixel size from seeing limit to diffraction limit, cuts sky background on ground by factor $\sim(D/\text{cell size})^2$

Image: Comparison of optical observational capabilities for the coming decades: ground versus space, Matt Mountain et al., 2009



Adaptive Optics (AO) Principles



- Proposed 1953, Horace Babcock
- Requires bright star(s) to focus on
- Classified development, 1960's, 70's
- Laser guide stars in upper atmosphere proposed, 1980's
- Wavefront sensor and deformable mirror compensate for turbulence, in closed loop control
- Turbulence is distributed in altitude
- Requires fast camera in wavefront sensor, fast computer, fast deformable mirrors with as many pixels as there are seeing cells – the hard technologies for AO!
- Result: most of light in near diffraction limited image core, remaining light has seeing PSF (arcsec)

Diagram: CfAO (Center for Adaptive Optics)

Hybrid Observatory for Earthlike Exoplanets

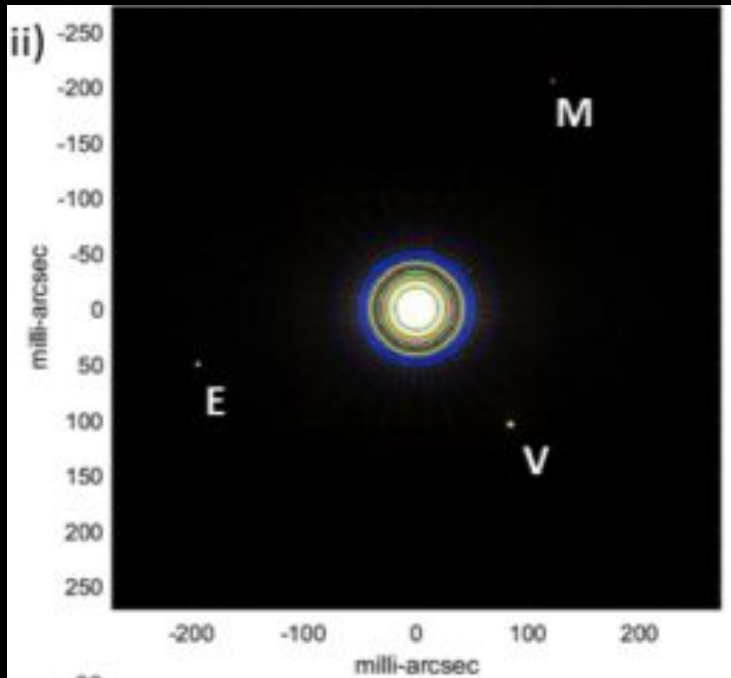
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Hybrid Observatory for Earthlike Exoplanets: Search for Earth 2.0

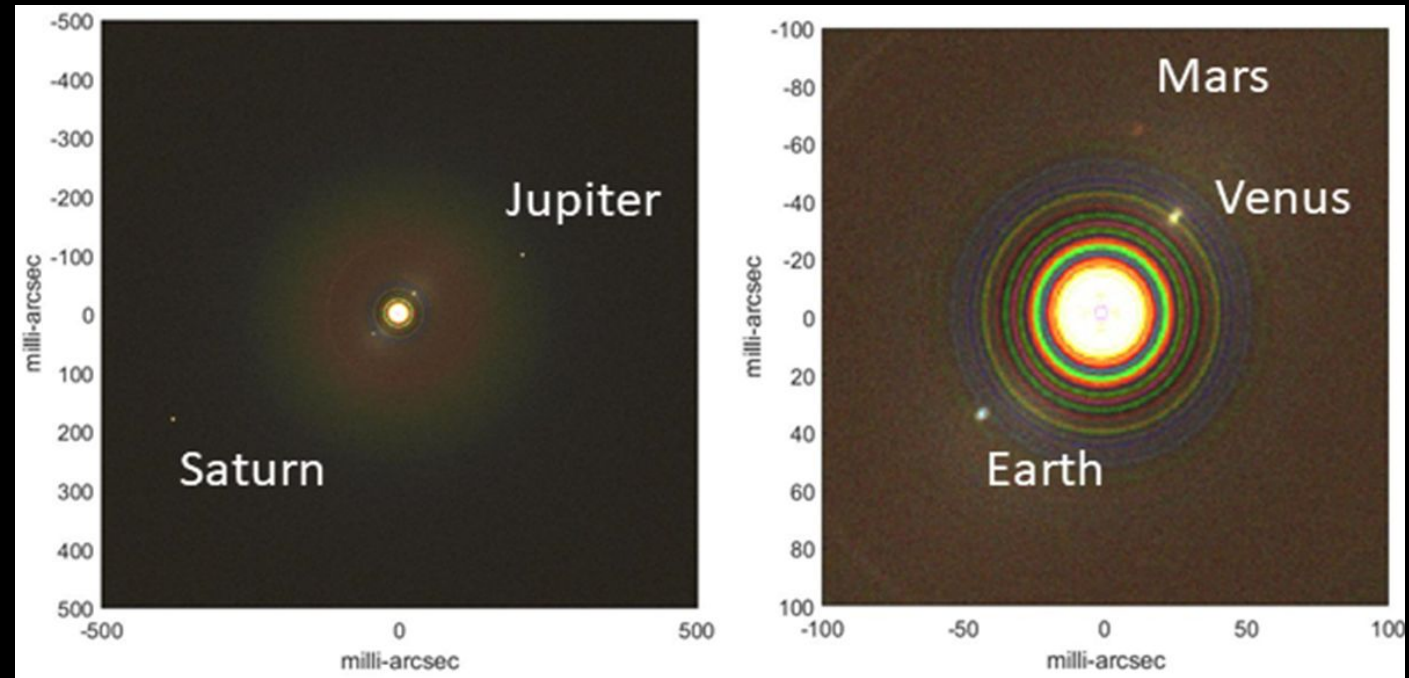
- Image reflected visible and UV light from Earth-like exoplanets around Sun –like stars
 - Top priority in exoplanet science, per Decadal Survey 2020
 - Sun lasts long enough, is not hostile
 - Earth is right size to have life
 - But: Sun is 10 billion times brighter than Earth!!
 - Measure orbit, size, temperature, atmosphere, surface features
- Obtain spectra of exo-atmospheres for signs of life: oxygen, water, ozone (not CO₂, sorry, no strong lines in visible band), and all other planets
- Look for variable planet brightness, as a sign of continents, oceans, weather, vegetation red edge
- Infrared is too hard: diffraction, atmospheric interference, needs huge cold space telescope or formation flying interferometer
- Much better imaging and sensitivity than much smaller, more costly, perfect, ultra-stable space telescope with coronagraph

Desired Results: images

Solar System at 5 pc in 1 minute



Solar System at 17 pc in 1 hour



Images by Stuart Shaklan with ELT and orbiting starshade

Mission Architecture

- Starshade casts a shadow of the star onto the telescope without blocking the planets
 - Huge distance: >170,000 km
 - Huge size: 100 m diameter
 - Inner working angle 60 mas at tips, 1 AU at 17 pc
 - Pointed petals suppress diffracted starlight
 - Laser beacon at center supports AO, and communications to telescope
 - Precise alignment within a few m: propulsion & control
 - Different orbit for each target star
- 39 m European or other ELT Telescope on the ground
 - Diffraction limited image quality with Single Conjugate Adaptive optics, few arcsec isoplanatic patch
 - Coronagraph blocks starshade light (leakage, sun glints, Earthshine)
 - Background limited $\text{SNR}^2 \propto t (D/s)^4/B$; t = time, D = diameter, s = star distance, B = background surface brightness
 - Cameras and spectrographs
 - Starshade shape resolved by telescope (3 m spatial resolution), and in near field
 - Sends alignment error info and commands to starshade

How it works: Mission Architecture

- Starshade appears to stop in front of star, astrostationary, held in place by jets
- Starshade casts shadow of star onto telescope without blocking planets
 - Laser beacon at center supports AO, and communications to telescope
 - Precise alignment within a few m: propulsion & control
 - Different orbit for each target star
 - Potential for refueling/replacement of propulsion, for long life and high yield
- 39 m European ELT Telescope on the ground ready soon; others coming
 - Single Conjugate Adaptive optics (SCAO); one wavefront sensor, on deformable mirror
 - Coronagraph blocks starshade light (leakage, sun glints, Earthshine)
 - Cameras and multiobject spectrographs
 - Starshade shape resolved by telescope (3 m spatial resolution), and in near field
 - Sends alignment error info and commands to starshade

Why Now?

- Found ultralight deployment concepts (NIAC support)
 - Reduced cost
 - Enables multiple missions & space test program
 - Increased yield
- Can avoid pulsed stationkeeping chemical thrusters
 - use hot gas
 - No shape recovery from pulses
- Relaxed tolerances make it feasible
 - Huge telescope resolves starshade shape
 - Internal coronagraph blocks starshade light
 - Enables ultralight deployment concept
 - Starshade constructible with normal engineering
- Telescope ready in ~5 years

Active Astrostationary Orbit

- Stop relative motion on line of sight from telescope to star at chosen time
 - Match position and velocity components perpendicular to line of sight at beginning of observation
- Choice of radius and radial velocity, governs perigee and period
- Repeat observation once/orbit: integer number of days
- Minimum 4 or 5 day period, > 170,000 km apogee, long ellipse
 - Go farther to observe off meridian, high declination, more opportunities per orbit, or for smaller Inner Working Angle
- During observation, use propulsion to match transverse component of acceleration of observatory toward Earth spin axis
 - Choice of hot gas or chemical engines, pulsed if there's interference
- Possibility of 3 observations each 5-day orbit
- Possibility to use a different telescope each time
- Full observing program tool by Peretz, published
- Target list and observing time are FUEL LIMITED: science strategy critical
- Low mass, big tanks, high Isp, high solar power needed, refueling/replacement desirable

Operations Concept: How You Use It

- Determine orbit progress
- Send commands to arrive at rendezvous
- Observe starshade position error with telescope
 - Direct imaging, then leakage around edge
- Establish closed loop starshade position control, using hot gas or chemical propulsion, and 2 way (laser?) comm link
- Take images with telescope, searching for planets
- Set up multiobject spectrometer for detected planets
- Take spectra, decide when to end exposure
- Decide on changes to next target list; is a revisit needed?
- End closed loop position control, send propulsion commands to aim for next target
- Repeat

Major Accomplishments since 2018 start - 1

- Calculated exoplanet spectra accounting for telluric absorption
- Completed Team X and Team A studies at JPL
- Solved orbit problem, built planning tool, calculated yield
- Found possibility of multiple observations each orbit
- Relaxed shape tolerances & stray light, due to telescope internal coronagraph (HOEE NIAC study) and resolved starshade image
- Studied constructible and inflatable starshades (2 current NIAC studies)

Major Accomplishments since 2018 start - 2

- Demonstrated visible band AO with orbiting laser beacon (LCRD) at Keck
 - Simplest possible: 1 sensor, 1 deformable mirror, single conjugate (SCAO); no upgoing lasers
 - No stray light: block laser with filter
- Spun off ORCAS mission study for AO
 - Will prove SCAO with the beacon at center of the starshade
- Proposed & approved Landolt mission with orbiting photometric standard (Plavchan PI at GMU)
- Learned of hot gas (prefer H_2) concept for stationkeeping, avoids visible plume and need for pulsed thrust, gated observations, and transient recovery
- Added servicing/refueling to mission concept for unlimited lifetime and yield

Starshade Requirements

- Central disk + pointed petals to apodize shadow
- Diffraction governed by Fresnel number $F = L^2 / (\lambda s)$, where L is characteristic size, and s is distance; $F=29$ for $L=50$ m, $0.5 \mu\text{m}$, 170000 km
- Numerical optimization for wide band tradeoffs
- Shape tolerances based on SISTER analysis code, depending on form of assumed shape error: orders of magnitude looser than for smaller telescopes
 - Keep shape tolerance during station keeping thrust, or after pulse recovery
 - Depends on performance of telescope coronagraph
 - Needs analysis and physical test models
- 2 or more layers for punctures ($\sim 0.1\%$ hole area?); sunlight and coherent starlight leakage
- Earth side black or specular for minimum Earthshine reflection
- Sharp edges for minimum solar glints (but not razor sharp)
- 3D structure hidden from telescope over $\pm 30^\circ$ range of tilt angles
- Sunlit portions mostly hidden from telescope
- Lowest mass; mass drives cost, launch vehicle choice

Telescope Requirements

- As large as possible: $(D/d)^4/B$ speed factor, where D = diameter, d = target distance, B is background light including Earth atmosphere, zodi, and exo-zodi
- Single Conjugate Adaptive Optics (SCAO) for moving laser beacon target, ELTm PSF ~ 3 milliarcsec
- Strehl ratio $>50\%$ for efficiency
- Dispersion correction better than PSF width; does it need 2 wavelengths for the beacon?
- Coronagraph to block starshade image (near field)
- Multiband camera with dichroics and simultaneous observations
 - Wavelengths 320-1000 nm would cover major bands of:
 - Oxygen,
 - Ozone,
 - Water, and
 - VRE (vegetation red edge from chlorophyll, if any)
- Multiobject spectrometer, set rapidly for multiple exoplanets
 - Choice of spectral resolution?
- Starshade position error sensor (imaging and leakage around edge)
- Upgoing laser? for closed loop communication

Three Starshade Deployment Concepts

- Classic method, JPL et al:
 - folded petals wrapped around spacecraft bus,
 - circular truss surrounds opaque center,
 - petals attached to truss,
 - Motor driven deployment
 - Can be optimized for lower mass
- Constructed in space: Gregg et al, NIAC Phase I.
 - Small robots, small parts, repetitive structure
- Inflated: Mather et al, NIAC Phase I; contract to OMP
 - Ribs with petals attached, attached to hub
 - Cable rigidization for definite shape

Spacecraft Requirements

- Deploy starshade, keep it nearly edge on to Sun during observations
- Laser beacon(s) and (?) photometric calibrator at center
- Normal orbit determination, maybe high altitude GPS
- Communicate with telescope for fine position error information, commands
- Position control within a few m, for dark shadow, closed loop including telescope
- SEP (solar electric propulsion), very large tanks, for orbit changes, Isp controls number of targets
 - Very large solar panels for high Isp; hundreds of kW
- Chemical or hot gas propulsion, for station keeping; large tanks, Isp controls observing time
- Attitude control, probably not rotating, but might change for retargeting
- Main jets thrust vector through center of mass
- Reaction wheels (?) and attitude control jets for orientation
- Jet plumes do not damage starshade
- Consider propulsion refueling or replacement, for unlimited target list

Known Observing Geometry for HOEE

- Sun $>18^\circ$ below horizon for darkest sky
- Near sunrise or sunset: 2 cases
- Target not too close to Sun: $>45^\circ$ above horizon for adaptive optics to work (elongation $> 45+18= 63^\circ = 90^\circ - 27^\circ$ depending on declination)
- 45° above horizon also good for orbit choice: lower in sky \square increased shade distance \sim proportional to $1/\text{projected velocity of observatory}$
- Starshade can be \sim edge on $+ 5^\circ$ to Sun, Sun never strikes Earth facing side, dark side is cold (design choice)
- Starshade $< 30^\circ$ from perpendicular to line of sight, otherwise shadow shrinks too much (design choice)
- Target not too far from the Sun: elongation $< 90^\circ + 30^\circ - 5^\circ = 90^\circ + 25^\circ = 115^\circ$, allows observations on meridian
- Equatorial target visible for 52 days each season, x 2 seasons
- Inner working angle inversely proportional to starshade distance; choice of orbit
- Planning tool written by Peretz & results published

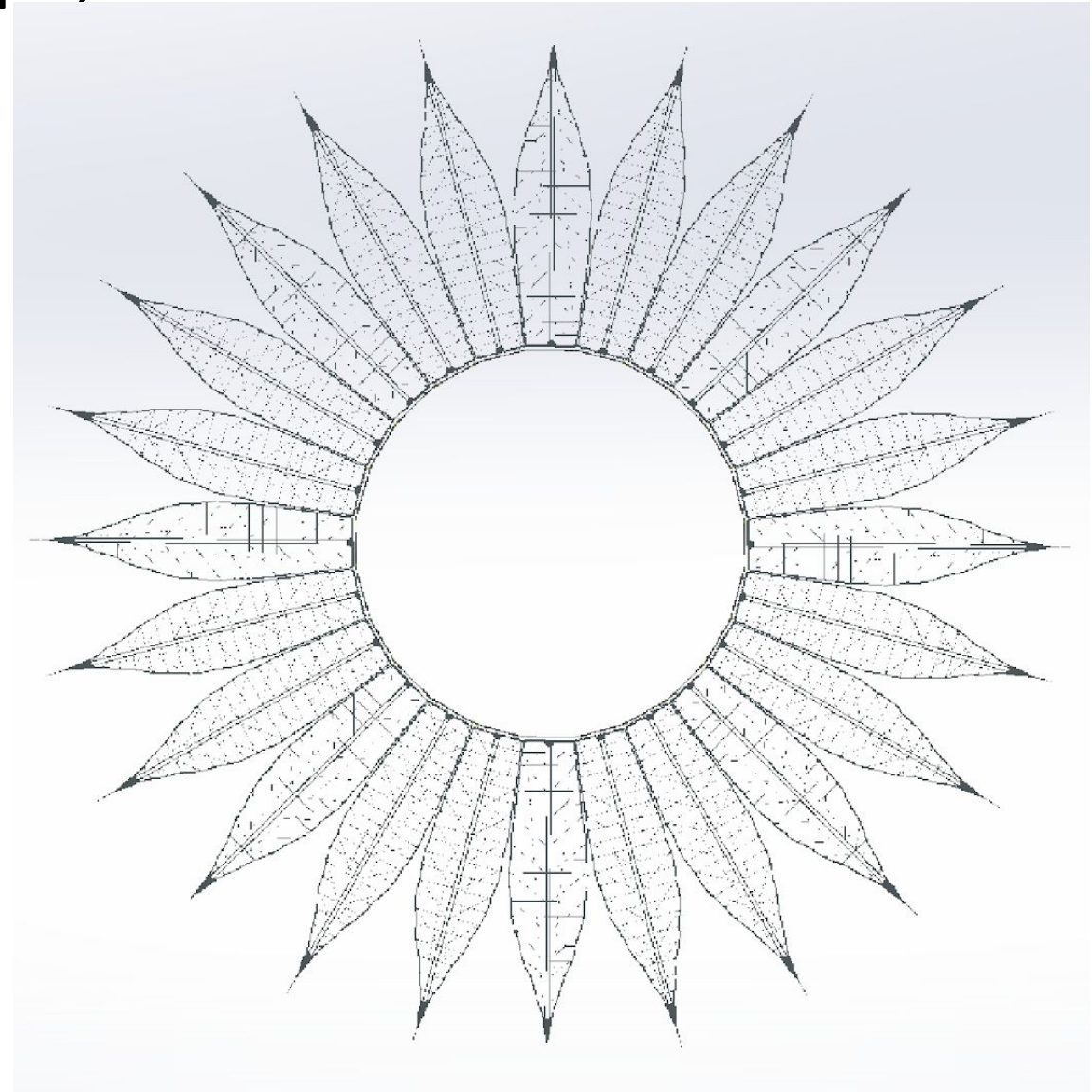
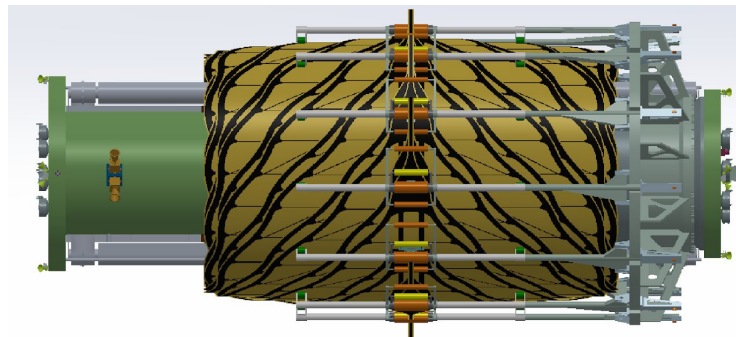
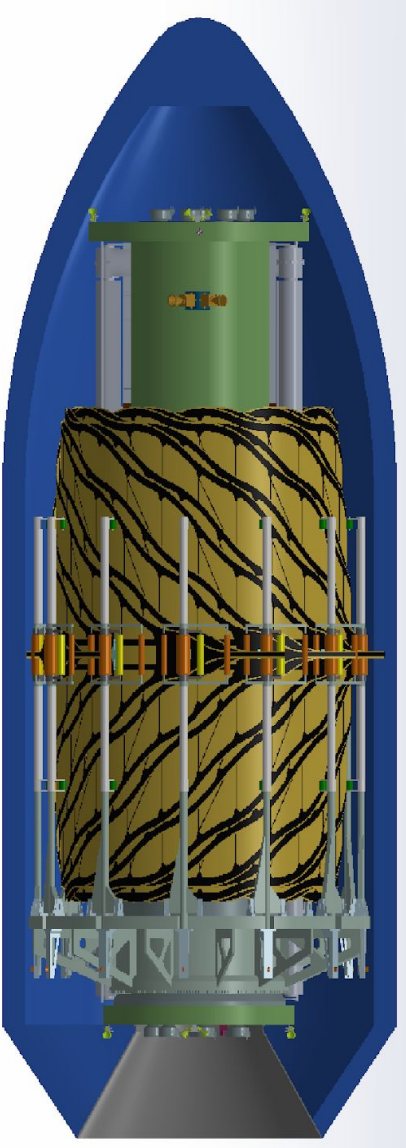
Potential Observing Schedule

- Each target visible 2 seasons: sunrise and sunset
- Up to 3 targets per orbit, about 12° apart
 - Would need enough propulsion to retarget in a day
 - About 200 chances/year
- Repeat observations to
 - get planet orbits (motion detectable in 5 days),
 - observe when far from star,
 - get brightness and color changes
 - Accept conflicts, weather, Moon interference $\sim 1/3$ of time
- Mean spacing of 200 targets in half of sky is $\sim 10^\circ$
- Visible region of sky rotates as Earth orbits sun
 - Requires enough propulsion force to keep up
- If not possible, longer mission required

Team X Concept extrapolated smaller starshades, included all parts for HOEE with ground telescope, but:

Did not fit launch capabilities

- Therefore:
- Reduce mass & volume, or
- Bigger rockets, or
- Enable refueling



Orbit Management for HOEE

- Orbit to match transverse observatory velocity
 - $v = \omega \times r \sim 6378 \text{ km} * 2 \pi * \cos(\text{latitude}) / 1 \text{ day} \sim 400 \text{ m/s}$
 - $v_{\text{perp}} = \text{LOS} \times v \sim 400 \text{ m/s}$ on meridian, $\sim 200 \text{ m/s}$ 60° off
- Distance $> 170,000 \text{ km}$ from Earth, or perigee is too low, can be increased to reduce inner working angle or observe far from meridian
- Cost of orbit change $\sim 30 \text{ m/s/}^\circ$ on sky
 - = Angular momentum/semiminor axis = velocity when passing the semiminor axis
 - confirmed by optimization codes
 - Reduced with special near-escape maneuvers and lots of time
 - Full circle 10.8 km/sec
- Cost of keeping up with the Sun, 30 m/s/day
 - Average acceleration $3.5\text{E-}4 \text{ m/s}$; for 3000 kg , $F = 1.05 \text{ Nt}$ (divided by duty cycle)
 - Implies SEP, high thrust, high power; specific impulse proportional to power
 - Or, go slower, can't observe all year
- Mean spacing between uniformly distributed targets = $\text{sqrt}(\text{frac} * 4 \pi / N)$; for fraction of sky = $\frac{1}{2}$, $N = 200$, angle = $0.18 \text{ radian} = 10^\circ = 300 \text{ m/s}$ per target

High Power Solar Electric Propulsion

- Orbit to match transverse observatory velocity
 - $v = \omega \times r \sim 400 \text{ m/s}$ (ω = Earth spin rate, r = Earth radius at observatory)
 - $v_{\text{perp}} = \text{LOS} \times v \sim 400 \text{ m/s}$ on meridian, $\sim 200 \text{ m/s}$ 60° off
- Distance $> 170,000 \text{ km}$ from Earth, or perigee is too low
 - Increase to reduce inner working angle
 - Increase to match lower projected observatory velocity far from meridian
- Cost of orbit change $\sim 30 \text{ m/s/}^\circ$ on sky = velocity at semiminor axis per radian
 - Full circle 10.8 km/sec
 - For large changes, boost to higher orbit first
- Cost of keeping up with the Sun, 30 m/s/day
 - Average acceleration $3.5\text{E-}4 \text{ m/s}^2$
 - Example for 3000 kg , $F = 1.05 \text{ Nt}$ (divided by duty cycle)
 - Implies SEP, high thrust, high power; specific impulse proportional to power
- If high power not available, then slower mission timeline

Hot gas or pulsed jets for station-keeping

- Station-keeping acceleration on meridian = $\text{LOS} \times (\omega \times v) \sim 0.03 \text{ m/s}^2 * \sin(\text{declination}) / \text{duty cycle (about 3 milli-g)}$
- On meridian, towards N or S pole
- Off meridian, add E or W components
- At 30° declination, need 108 m/s/hr or 2160 m/s for 20 hrs
- Prefer adjustable steady thrust with hot hydrogen (no visible emission)
 - Example $F = 3000 \text{ kg} * \text{accel} = 45 \text{ Nt}$.
 - Hundreds of kW, suggests “thermal battery” with phase change material (liquid boron), $I_{sp} 800 \text{ sec}$.
- Chemical jet plumes might be bright with “interesting” molecules 40 sec period, $\pm 6 \text{ m}$
 - Gated observations and pulsed jets
 - Bang-bang control with max error $\pm 6 \text{ m}$ in $t = \sqrt{2 \text{ s} / a} = 40 \text{ sec}$ at 30° , implies cycle time and shadow size
 - Fast shape recovery after pulses
 - For duty cycle 0.1, declination 30° , $m = 3000 \text{ kg}$, $F = 450 \text{ Nt}$

Electric Propulsion Example

- $F = \text{force} = (dm/dt)v$, $v = \text{exhaust velocity} = g \text{ Isp}$
 - $m = \text{mass}$, $g = \text{gravitational constant}$, $\text{Isp} = \text{specific impulse}$
- Power consumption = $P = (1/2)(dm/dt)v^2/\epsilon$
 - $\epsilon = \text{efficiency} = 0.5$
 - $P = F v / 2 \epsilon = F g \text{ Isp} / 2 \epsilon$
 - $P = 2 \text{ Nt} * 9.8 \text{ m/s}^2 * 8000 \text{ sec} / (2 * 0.5) = 157 \text{ kW}$
 - Compare 60 kW on Lunar Power Propulsion Element
 - $\Delta V = g \text{ Isp} \ln(m_2/m_1)$
 - ΔV proportional to P !
 - Maximize solar array size
- Thermal rocket similar (e.g. hot hydrogen)
 - $P = 45 \text{ Nt} * 9.8 * 800 / (0.5 * 2) = 353 \text{ kW}$ (use stored heat)

Tall poles, unknowns

- Mass of deployed starshade; cost driver
- Starshade light rejection by telescope coronagraph, how good is it?
- Feasibility of cold or hot gas for station keeping, especially hydrogen
- Shape recovery after thrust pulses; need for active control?
- Shape tolerances; active control?
- Review of requirements: if we build it, will it work?
- Review of science: if we build it, will scientists be happy?
- Example mission concept, including geometry, deployment, thermal considerations, solar arrays, propulsion modules, protection from thruster plumes, telescope hardware with coronagraph, instruments, AO, operations concept with alignment acquisition
- Servicing concepts vs multiple missions for higher yield
- Technology demonstrations
- Test programs
- Precursor science, need to know where to look

Driving Unknowns

- Stationkeeping propellant, plume visibility
 - If invisible, then no need for pulsed thrust
- Architecture for refueling or replacing propulsion module
- Cost tradeoff of refueling, replacing modules, or multiple complete missions
- Performance of ground coronagraph
 - sun glints : edge sharpness
 - diffracted starlight: shape tolerance
 - Earthshine: blackness requirement
- Access to UV science, e.g. ozone (depends on telescope AO)

Science Questions

- Precursor science: EPRV, ORCAS, ExAO boosted by ORCAS, astrometry, exo-zodi measures, all ways to know where and when to look
- When will SCAO work on ELT?
- Mission simulation, yield calculations vs. HWO, including parameter retrieval through terrestrial line blocking, and value of UV if possible
- Design Reference Mission: What can we promise?
- Minimum detectable column density of O_2 and O_3 ? (cf. blockage by Earth atmosphere; what's our performance limit?)
- What does a young Earth look like, before oxygenation?
- Community engagement: will a new science team have different use cases and priorities?

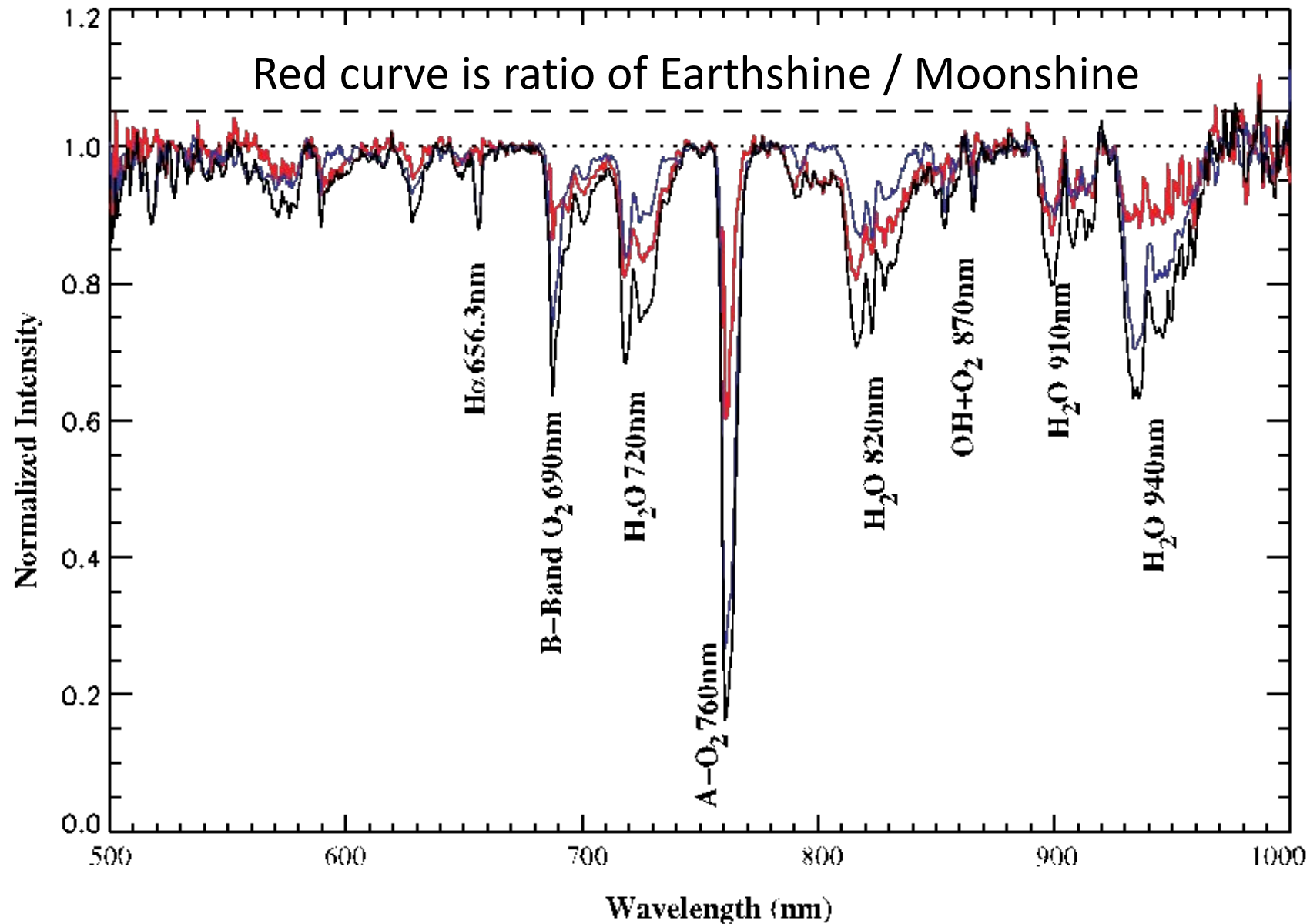


FIG. 3. Normalized moonshine spectra (*blue*), earthshine (*black*), and their ratio (*red*) for 2003 November 19. The main gas absorption bands as well as other features and their central wavelengths are indicated. Note how the solar H α line disappears in the ES/MS ratio.

Unknowns and Ideas

- UV limit for ozone: can we see exo-ozone?
- Visibility of jet plumes, continuum and spectra. Could we avoid pulses?
- Erosion of plastic by jets
- Servicing concept geometry: refueling, or separating main propulsion modules from starshade during station keeping
- Value of very high R spectroscopy for parameter retrieval, especially if detectors are perfect photon counters
- Inflatable vs deployable vs construction
- Is low mass still important given low cost launches and refueling

KISS Study Objectives

- Review progress
- Discover problems, propose solutions. Any show-stoppers?
- Build teams for next steps: NIAC phase II proposal, etc.
- Discuss what to propose:
 - DRM, use case, including number of targets, schedule of revisits
 - Deployment or construction
 - Shape accuracy requirements based on ELT coronagraph rejection estimates
 - Viewing angle requirements
 - Spacecraft concept decisions
 - Propulsion
 - Servicing, refueling, replacement
 - Configuration

Steps to Earth 2.0!

- Complete NIAC studies (Mar 2026) & KISS study; propose Phase II NIAC April? 2026
- Propose and fly ORCAS for adaptive optics on ground, demonstrate high angular resolution and sensitivity on Keck and ELT
- Develop instrument concept for ground telescopes
- Develop preliminary team agreements: NASA, NSF, ESO, ESA, etc.
- Technology maturation: NIAC phase II; test units
- Mission study for starshade: NIAC phase III
- Recommendation of Decadal Survey, 2030
- Presentations to fund sources (not just NASA)
- Flight mission proposal, selection, phases A, B, C, D, E
- Announce discovery of Earth 2.0