# An Externally Occulted Telescope for Exoplanet Characterization

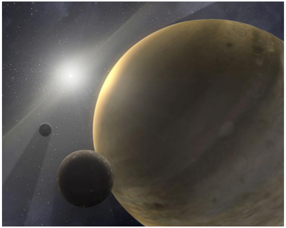
L. Childers, K.D. French, R. Kerviche, T. Schad, E. Schneider, C. You

Modern Astronomical Optics Team Project 3

April 26, 2012

Image courtesy Webster Cash

# Project Goals



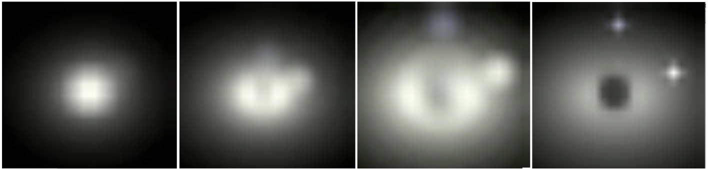
- Image Earth-like planets with a non-coronagraphic telescope with an external occulter
- Use spectroscopy to characterize the planets
- Use photometry to detect oceans, continents, polar caps, clouds, etc.
- Several issues with observing exoplanets include their close proximity to host stars and relative dimness

# Motivation for High-Contrast Exoplanet Studies

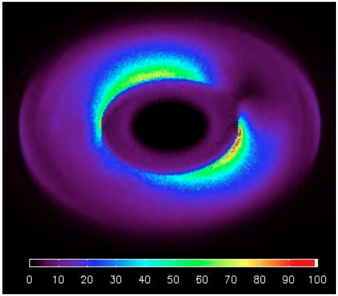
## What problems do we try to address?

1. Planetary system formation
2. Learn more about each known type of planet
3. Identify new types of planets
4. Identify habitable planets
5. Find life signature (spectroscopy)
6. And a lot more...

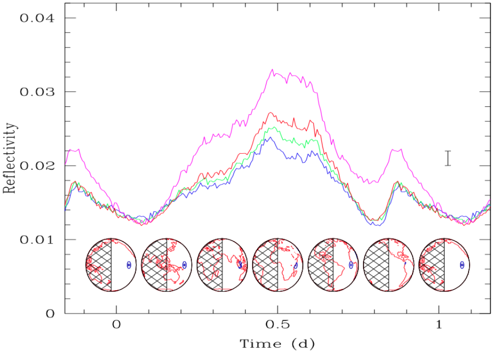
# Photometric Imaging of Exoplanet Systems



- Exozodical light can reveal detailed dynamics of planetary system and perhaps some history. (Kuchner et al 2007)

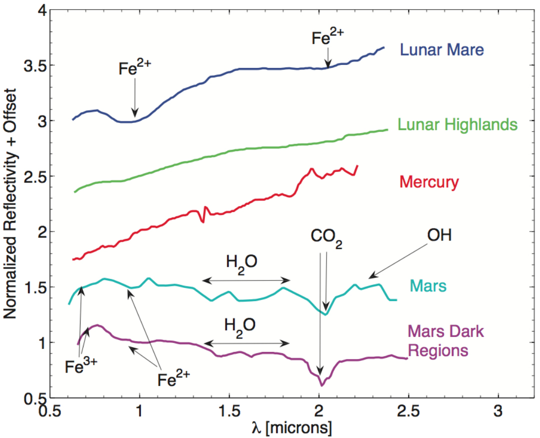


# Photometric Variability of Exoplanet Systems



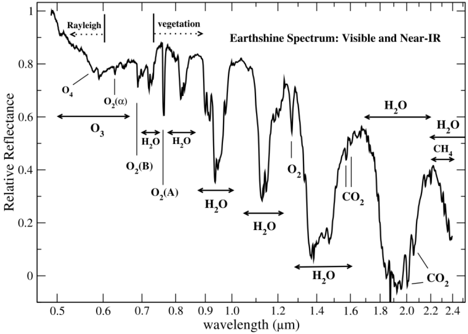

- Variability can reveal geological features on terrestrial planets
- Red edge vegetation signature reveals life

# Comparative Reflection Spectroscopy



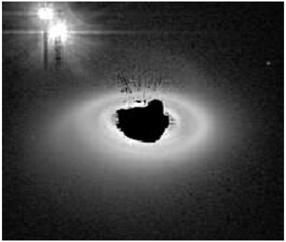

- Reflection spectra offers comparison with solar system bodies to characterize observed planets.

# Spectral Signatures of HZ Life



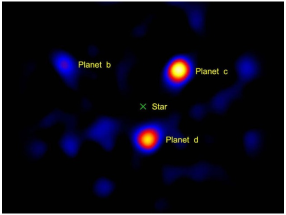

- Comparison with Earth reflectance spectrum to reveal life.
- Oxygen molecular signature at 760 nm due solely to plant life on Earth.
- No other known mechanism to produce O2 in HZ planetary atmospheres is currently known.

# High-Contrast Imaging Techniques



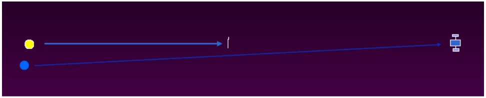
- In visible light, the Earth is about 10 billion times less bright than the Sun.
- Imaging techniques must include the removal of the starlight to isolate the light from the planet
- This involves using occulters to block the host star's light to better observe exoplanets

- Methods include using an external occulter (shadow cast over the telescope) or internal coronagraph (blocks stray light that is Fresnel diffracted around an occulter)



# External Occulter Proposal

- Use an external occulter to block the light from the star, while allowing the planet's light to reach a non-coronagraphic telescope.
- The occulter will be attached to a spacecraft that can be moved to observe different targets.
- Multiple occulters can be used to increase the efficiency of the system.



# Advantages of Internal Coronagraphs

- Arbitrary shape
- High theoretical contrast
- Operations are well understood and simple
- Low cost
- Almost no limit to observation rate (just slew telescope)
- Unlimited lifetime

# Disadvantages of Internal Coronagraphs

- Technically challenging ($10^{-10}$ contrast needs near perfect optics)
- Can only be used with some telescope science instruments
- Target must be placed in a specific location in the image plane
- Spot size invariable (not target optimized)
- Design fixes shape

# Advantages of External Occulters

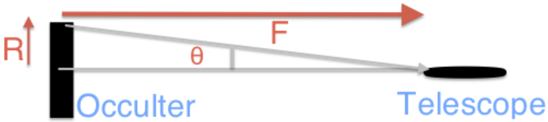
- No internally scattered light
- Precisely control occulting spot location
- Can place target anywhere in the image plane
- Useable with any science instrument
- Some shape change capability
- Generally good light suppression

# Disadvantages of External Occulters

- Cannot make some shapes
- Highest light suppression requires bulky, distant, slow occulters
- Separate spacecraft for telescope and occulter
- Operations fairly complicated
- High cost for large occulters
- Observation rate limited by travel time
- Limited lifetime

# External Occulters

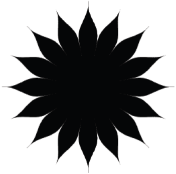
- Difficulty increased with increasing distance from telescope, but less precision required
- For large external occulter, want sum of phases through occulter to be minimized
- $\theta \sim m\lambda/R$
- For typical $\theta$ required to view planets, visible light, and $m \geq 10$, $R$ must be at least 20m (Cash, 2006)
- This $R$ and $\theta$ requirement places $F \sim 40,000$ km.



# Petal Shapes

- Design chosen to minimize diffraction from star
- Occulter shape design has two features: opaque until some radius $a$, then petals to increase transmission with $R$ to edge $b$.
- $A(R) = 1 - e^{-[(R-a)/b]^n}$ for $R > a$
- Results in suppression ratio

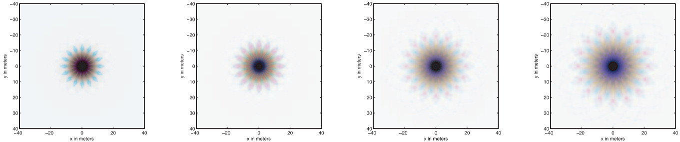
  $S \leq (n!)^2(\lambda F/2\pi ab)^{2n}$ (Cash, 2006)



Cash, 2006

# Petal Shapes

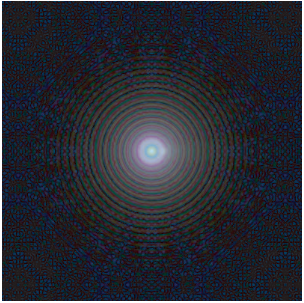
## Example Results

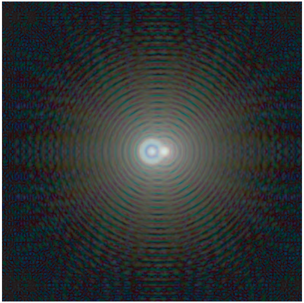



- From Vanderbei+ (2007), study of shadows cast by petal-shaped occulters at different distances

# Petal Shapes

## Example Results

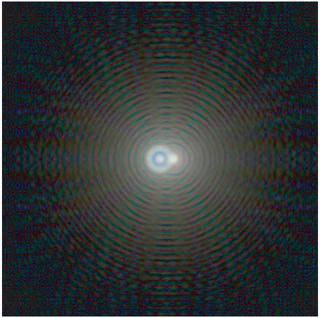




- From Vanderbei+ (2007), simulated observations with petal-shaped occulter. Left image: 22 meter occulter at 66,000km. Right image: 25m occulter at 72,000km.

# Design for observing exoplanets

- Optimal design calculated in Vanderbei+ 2007:
- 4m Telescope, 0.06" star-planet separation, $10^{10}$ contrast, broad wavelength observations
- Optimal occulter diameter is 50m, positioned 72,000km away from telescope



Vanderbei, 2007

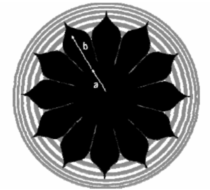
# Performance Quantification

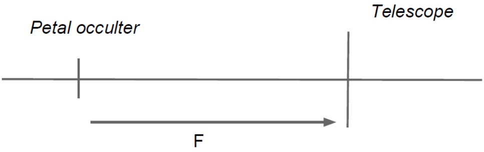
## Total Flux at Detector

Flux of the star: $F = F_0 \cdot 2.52^{-m}$

Occulter Attenuation (Cash, 2006): $S \leq (n!)^2 \left(\frac{\lambda F}{2\pi ab}\right)^{2n}$

$F_{planet} = F_{star} \cdot 10^{-10}$




- $\lambda = 0.64\mu m$
- $a = b = 12.5m$
- $n = 6$
- $F = 50000km$
- R star of magnitude 8

# Performance Quantification - Anticipated SNR

## Results

$S \leq 7.38 \times 10^{-13}$

$F_{star} = 2.89 \times 10^{7} ph\ s^{-1}\ m^{-2}\ \mu m^{-1}$

$F_{planet} = 2.89 \times 10^{-3} ph\ s^{-1}\ m^{-2}\ \mu m^{-1}$

$F_{star,filtered} = 2.07 \times 10^{-5} ph\ s^{-1}\ m^{-2}\ \mu m^{-1}$

For a 5 meter telescope, an integration time of 1 hour:

$F_{planet} = 204\ ph\ \mu m^{-1}$ -> Poisson noise: 14.3 $ph\ \mu m^{-1}$ -> **SNR** $= 14.3$

$F_{star,filtered} = 1.46\ ph\ \mu m^{-1}$

# Performance Tolerances

*Sensitivity of the occulter (from Cash, 2006) :*

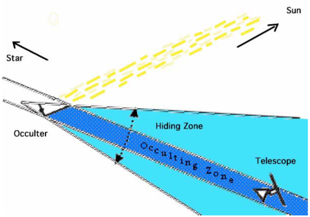
- **Lateral position** (center of the mask with respect to the intersection between the optical axis of the telescope and the plane containing the mask) : 20% of the starshade area $\approx$ 10% of the diameter $a$ (primary radius of the petal shape).
- **Pitch and Yaw angles** can be considered as the same error. After a mathematical demonstration the author show that, to the first order this parameters have little effect on the quality. He also presumes that the mission will be able to control this within a range of few arc-minutes.
- **Depth of focus** is linked with the tolerance on the wavelength as a linear relation. The author assume a margin of 10% on $F$ (as on the wavelength) but we might need a more precise value for spectroscopy.
- Other parameters include radial error in the petal shape, truncation of petal, opacity (or presence of holes in the mask : $A_{Hole} < \frac{\pi \lambda F}{\sqrt{S}}$).

# Mission Location: Space-based or Mixed?

- Advantage of external occulter -> can work for any telescope as long as shadow covers full aperture
- Biggest Challenge -> Establishing and maintaining proper alignment!
- Large distance between occulter and telescope make it impossible to do this only from the ground
- Difficult to mix space-based occulter + ground-based telescope (though studies have considered a telescope at south pole with relay spacecraft in geostationary orbit above)
- Alignment challenges and need for long term exposure stability calls for a space-based mission with 2+ spacecraft (one telescope/one occulter/+)

# Scattered Light Orbit Constraints

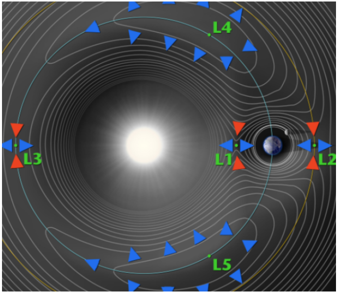
- Occulter fully opaque to target, but still can scatter sunlight into aperture. Options to mitigate:
  1. Use an additional shading device (i.e planet's umbra and/or additional artificial shader)
  2. Minimize amount of scattered sunlight via observing geometry




- Additional shading device difficult to achieve without considerable limitations
- Use Geometry ->Orbit designed such that telescope-occulter-solar angle is nearly 90 degrees

# Telescope-Occulter Location at L2

- New Worlds Observer/Imager concept study identified the L2 point to be probable deployment location for telescope-occulter coupled system.
- Closer proximity to Earth allows higher data transfer rates to/from spacecraft (better control)
- Telescope spacecraft can be put in meta-stable orbit with only minor orbital-corrective burns



# Mission Targeting and Control

- Target acquistion and alignment control is very challenging for this mission
- The finest alignment requires few meters control in lateral direction w.r.t. telescope-occulter LOS
- High precision astrometric control plus Doppler (RF) ranging intra spacecraft/DSN likely needed
- Station keeping complicated by solar radiation pressure plus Earth/Moon tides
- Trajectory and target scheduling must meet propellent and power restraints.
- SEP and/or combo SEP/chemical -> balance need for target changes version station keeping

# Concluding Remarks

- Newly designed occulters allow suppression of stellar light to below $10^{-10}$ within the central portion of its shadow.
- Coupled with $D > 4m$ aperture telescope, exoplanet imaging photometry and spectroscopy are possible.
- Greatest challenges include mission control and trajectory design. High precision necessary for necessary alignment
- In the future, this concept coupled with an interferometer will give us our first resolved picture of planetary surfaces in other worlds.

# Single of Multiple Occulters?

## Single Occulter:

- Lower cost (although the majority of the cost lies within the telescope)
- Would have to wait $\sim$ 2 weeks for the occulter to move into a new LOS

## Multiple Occulters:

- Increasing number of occulters increases project cost
- While one target is being observed, an additional occulter could be moving into position for the next target significantly increasing observing efficiency
- Second occulter could be sized/shaped differently to allow more flexibility in IWA achievability.

As the cost of an additional occulter would likely less than double the project cost but at least double the observing efficiency, multiple occulters should be used if possible.

# References


- "JPL Helps Shoot for the Moon, Stars, Planets and More." NASA Jet Propulsion Lab http://www.jpl.nasa.gov/news/features-print.cfm?feature=1619
- "HST Hubble Reveal complex Circumstellar Disk" http://hubblesite.org/newscenter/archive/releases/2003/02/image/