Coronagraphs and Starshades for Imaging Planets from Space

“I should disclose and publish to the world the occasion of discovering and observing four Planets, never seen from the beginning of the world up to our own times, their positions, and the observations . . . about their movements and their changes of magnitude; and I summon all astronomers to apply themselves to examine and determine their periodic times. . . .”

*Galileo Galilei, March, 1610*

(convicted of heresy, 1633
House arrest until his death.
Sentenced rescinded and
public regret, October, 1992)

N. Jeremy Kasdin
Princeton University

2009 Sagan Symposium

Pasadena, CA  12 November, 2009
Are we Alone?

- How do planetary systems form and evolve?
- So far, we have only observed the “tip of the iceberg”, need to detect lower mass planets and zodiacal light.
- What are the properties of planets?
  - Are there novel types of planets not seen in our solar system (e.g., water planets)?
- Are there other habitable planets?
- Detection of science of life

Only the direct imaging of planets can address all of these questions!
Prediction

• Sometime in the next four years, Kepler will announce the detection of significant numbers of Earth-like planets around typical stars.

• Astronomers and the public will ask:

“Can we see another Earth?”
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We are going to focus today on how to do it from space.
Prediction

We choose to . . . do [these] things, not because they are easy, but because they are hard, because that goal will serve to organize and measure the best of our energies and skills, because that challenge is one that we are willing to accept, one we are unwilling to postpone, and one which we intend to win, and the others, too.

John F. Kennedy
Rice University, 1962

We are going to focus today on how to do it from space.
Direct Imaging Exoplanet Science

Can we find life if it exists?

• Detect Earthlike planets in the habitable zone (as many as possible)
• Characterize their spectra from 250 - 1000 nm
• Revisit to characterize orbits and detect seasonal variations
• Characterize gas giants and outer RV planets
• Characterize circumstellar disks and dust
• Mass and radius?

And it would be nice to do a rich collection of astrophysics!
How We See The Stars

Really Far (> 10 pc)

The Star

The Telescope

Thursday, November 12, 2009
Unfortunately, the planet would be right here (and about 10 billion times dimmer in visible light)
Unfortunately, the planet would be right here (and about 10 billion times dimmer in visible light)
The Contrast Ratio Problem

At 10 pc, angular separation is 100 marcsec

- Visible
  - Earth/sun $\sim 10^{-10}$
  - Zodi small

- Infrared
  - Earth/sun $\sim 10^{-7}$
  - Zodi large
The Contrast Ratio Problem

At 10 pc, angular separation is 100 marcsec

Traub & Jucks
Solution: Change the optical path of the starlight to create “High Contrast” in final image.
Solution: Change the optical path of the starlight to create “High Contrast” in final image.

Metrics

• Contrast => Residual Q (planet / background)
• Inner and Outer working angle
• Throughput (absolute and relative)
• Observing Season
• Maximum integration time / Limiting Delta-mag
• Speckle stability
• Zodi Confusion

![Graph showing contrast over wavelength]
Solution: Change the optical path of the starlight to create “High Contrast” in final image.

Metrics

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• Inner and Outer working angle
• Throughput (absolute and relative)
• Observing Season
• Maximum integration time / Limiting Delta-mag
• Speckle stability
• Zodi Confusion

A careful error allocation is necessary to ensure the residual background is comparable to the planet.
Three Classes of Solutions

- Nulling Interferometers
- Internal Coronagraphs
- External Occulters
Internal Coronagraphs
Block starlight or modify PSF internal to telescope

**Amplitude in Image Plane**
- Lyot coronagraph
- Bandlimited Lyot

**Amplitude in Pupil Plane**
- Apodized Pupil
- Shaped Pupils
- APLC
- PIAA

**Phase in Image Plane**
- Four quadrant phase mask
- Vector Vortex coronagraph
- Achromatic interference coronagraph

**Phase in Pupil Plane**
- Visible nuller

*This list is not comprehensive.*
## Internal Coronagraphs

Block starlight or modify PSF internal to telescope

<table>
<thead>
<tr>
<th>Amplitude in Image Plane</th>
<th>Amplitude in Pupil Plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Lyot coronagraph</td>
<td>• Apodized Pupil</td>
</tr>
<tr>
<td>• Bandlimited Lyot</td>
<td>• Shaped Pupils</td>
</tr>
</tbody>
</table>

**REMEMBER:** It is all about taking a Fourier Transform!

<table>
<thead>
<tr>
<th>Phase in Image Plane</th>
<th>Phase in Pupil Plane</th>
</tr>
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<tbody>
<tr>
<td>• Four quadrant phase mask</td>
<td>• Visible nuller</td>
</tr>
<tr>
<td>• Vector Vortex coronagraph</td>
<td></td>
</tr>
<tr>
<td>• Achromatic interference</td>
<td></td>
</tr>
<tr>
<td>coronagraph</td>
<td></td>
</tr>
</tbody>
</table>

*This list is not comprehensive.*
Which means . . .
Which means . . .

You can’t beat the uncertainty principle
Which means . . .

You can’t beat the uncertainty principle

which limits your resolution (and inner working angle)
Which means . . .

You can’t beat the uncertainty principle

which limits your resolution (and inner working angle)

And it depends upon wavelength
Which means . . .

You can’t beat the uncertainty principle

which limits your resolution (and inner working angle)

And it depends upon wavelength

which limits your bandwidth
Which means . . .

You can’t beat the uncertainty principle

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And it depends upon wavelength

which limits your bandwidth

And getting enough photons would be nice!
The “Lyot” Coronagraph

The apodizer (field occulter) blocks most of the light from the star
Two Discoveries

A suspected Brown Dwarf orbiting 15 Sge. Image taken at Gemini Observatory/University of Hawaii

Fomalhaut b, the first imaged planet (taken from the Hubble Space Telescope)

Thursday, November 12, 2009
Pupil Apodization to Reshape PSF

\[ E(\xi, \zeta) = \int \int e^{i(x\xi + y\zeta)} A(x, y) \, dy \, dx \]
Shaped pupils: $A(x,y)$ is zero-one valued (holes in masks)

Advantages:
- simple to manufacture
- inherently broadband
- minimally sensitive to aberrations
- no off-axis degradation of PSF

Disadvantages:
- throughput (though roughly the same as 8th order Lyot coronagraph)
- IWA (better IWA can be achieved through less discovery space or greater simplicity)

Pupils designed via optimization under certain constraints
Aluminum coated side

400µm

200nm Al coating

50µm

125µm

The narrowest opening may be as small as 2 µm

Optical images

Aluminum coated side

uncoated side

Made via Deep Reactive Ion Etching (DRIE)

Courtesy of K. Balasubramanian (6265-130)
Contrast Measurement at 633nm

- Contrast:
  \[ \sim 10^{-5} \text{ @ } 4 \frac{\lambda}{D} \]
  \[ \leq 10^{-6} \text{ @ } 7 \frac{\lambda}{D} \]
Phase Induced Amplitude Apodization (PIAA)

 Nearly 100% throughput
 100% search area
 small (<2 lambda/d) Inner Working Angle

Pupil Mapping for Apodization

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Uncorrected Pupil Remapped Image

Contrast ~6e-4

Conventional image (computed)

PIAA image (obtained in the lab). White circle shows the area of the image that would be lost if we had done our apodization with a mask.

PSF projected On Sky

Thursday, November 12, 2009
What is the biggest problem? Wavefront Error

Phase Aberrations

Amplitude Aberrations

\[ I(\xi, \eta) = |F \{ [1 - \beta(x, y)] A(x, y)e^{i\phi(x, y)} \}|^2 \]

Amplitude aberration  Phase aberration

Thursday, November 12, 2009
What is the biggest problem?
Wavefront Error

Effects of the Atmosphere

Because of the atmosphere, big telescopes don’t resolve any better than small ones!
Current & Future Ground Telescopes use AO

Neptune

Star Image

Without Adaptive Optics

With AO

Images and Video from UC Santa Cruz Adaptive Optics course.

Thursday, November 12, 2009
Current & Future Ground Telescopes use AO

Images and Video from UC Santa Cruz Adaptive Optics course.
Wavefront Control

Control Algorithms:
- Speckle Nulling
- Energy Minimization
- Electric Field Conjugation
- Stroke Minimization

Estimation Algorithms:
- DM Diversity
- Gerchberg-Saxton

Thursday, November 12, 2009
Experimental Results: Symmetric Dark Holes

DM Diversity:

Two-Camera:
All four coronagraph types have been tested in JPL’s High Contrast Imaging Testbed
Bandlimited Lyot

Four coronagraph types have been tested at HCIT
The single largest contrast term in the error budget is the 'Mask Error' term at the bottom of Table 4. As noted above, restricted to thermally-induced motions of 10 nrad and 100 nm in tilt and translation, respectively. These motions with the optic diameter relative to the downstream optics. Beam motion occurs on the secondary mirror but it is only 5 nm of motion along the line-of-sight, and 65 nm of lateral motion. With the system stop placed at the DM, most of the walk and aberrations. The beam walk is a far worse effect, again dominated by optics M3-M7. Thermal motions of the Finally, structural deformation (the motion of optics relative to one another, with the PM fixed) contributes both beam aberrations. The small primary mirror aberrations do not significantly incr aberration amplitude, the downstream optics play only a small role in the overall contrast. Mask errors combined with smaller (amplitude = 0.3 mas and offset = 0.3 mas). The major contributors are 0.2 nm r.m.s. of coma (contrast = 2.7x10^-11). Z10 (trefoil), but higher order modes (Z11, spherical aberration and above) scatter light at much lower aberrations.

Table 4 is a roll-up of dynamic contrast contributors, including bending of the optics, beam walk across all optics, and pointing error that remains uncompensated by the secondary mirror. Jitter: 10 nrad, 10 nm Jitter: 10 nrad, 10 nm Thermal: 10 nrad, 100 nm Thermal: 10 nrad, 100 nm Jitter: 10 nrad, 10 nm Jitter: 10 nrad, 10 nm

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ACCESS observatory: 1.5 meter - unobscured off-axis gregorian telescope

TPF-C: 8 meter - unobscured, elliptical off-axis telescope
• Inner working angle depends on wavelength and aperture.
• Most require off-axis telescope and monolithic mirror.
• Most have lower throughput.
• All require active wavefront control and stable telescope.
• Limited outer working angle.
• Bandwidth limited by wavefront control system.
• Rapid retargeting.
• Large sky angles.
• Little or no UV capability (unlikely to get ozone cutoff).
What about mother nature’s coronagraph?

Use an external occulter to block the light.
What about mother nature’s coronagraph?

Use an external occulter to block the light.

In 1962, Lyman Spitzer at Princeton first proposed high contrast imaging with an artificial external occulter.
Unfortunately, the diffraction problem is still there

Poisson’s Spot
Unfortunately, the diffraction problem is still there

**ANSWER:** Apodize the occulter!

Poisson’s Spot
External Occulters

• Spitzer (1962) first proposed using an apodized starshade.
• Others followed, Boss (Copi & Starkman (2000)), Umbras (Schultz (2003))
• Copi & Starkman found general solution to Fresnel integral on axis.
• Vanderbei et al. (2007) found optimal apodization functions.
• Spitzer & later Marchal (1985) first suggested using a \textit{shaped} starshade.
• Simmons (2005) suggested occulters as complements to shaped pupils.
• Cash (2006) proposed a starshaped starshade.
Electric fields

Using Babinet’s principle, the field due to a transmissive occulter is:

$$ E(\rho, Z) = E_0 e^{\frac{2\pi i Z}{\lambda Z}} \left( 1 - \frac{2\pi}{i\lambda Z} \int_0^R A(r) J_0 \left( \frac{2\pi r \rho}{\lambda Z} \right) e^{\frac{\pi i}{Z} (r^2 + \rho^2)} r dr \right) $$

We can use this to calculate the field for a given apodization, A[r], or we can solve an optimization problem to find A[r].
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We can use this to calculate the field for a given apodization, A[r], or we can solve an optimization problem to find A[r].

But apodized occulters are really hard to make . . .
Opaque Occulter

Remember Starshaped Masks?

\[
E_{o,\text{petal}}(\rho, \phi) = E_{o,\text{apod}}(\rho)
\]

\[-E_0 e^{\frac{2\pi iz}{\lambda}} \sum_{j=1}^{\infty} \frac{2\pi(-1)^j}{i\lambda z} \left( \int_0^R e^{\frac{\pi i}{\lambda z} (r^2 + \rho^2)} J_{jN} \left( \frac{2\pi r \rho}{\lambda z} \right) \frac{\sin \left( j\pi A(r) \right)}{j\pi} r dr \right) \times (2 \cos \left( jN(\phi - \pi/2) \right)) \]
An Optimal 16-Petal Design
An Optimal 16-Petal Design

They’re actually still pretty hard to make . . .

Thursday, November 12, 2009
Starshade Requirement Allocation

<table>
<thead>
<tr>
<th>Manufacture, Deployment, or Control</th>
<th>amplitude</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Petal r.m.s. shape vs design, $1/f^2$ power law</td>
<td>100 um</td>
<td>Dominated by low spatial frequencies, $p = 10$ m at maximum width, decreasing with petal width</td>
</tr>
<tr>
<td>2 Petal proportional shape error</td>
<td>80 um</td>
<td></td>
</tr>
<tr>
<td>3 Petal length (clipping at tip)</td>
<td>1 cm</td>
<td></td>
</tr>
<tr>
<td>4 Petal azimuthal position</td>
<td>0.003 deg</td>
<td>1 mm at petal tip</td>
</tr>
<tr>
<td>5 Petal radial position</td>
<td>1 mm</td>
<td></td>
</tr>
<tr>
<td>6 In-plane rotation about base</td>
<td>0.06 deg</td>
<td>1 cm at petal tip</td>
</tr>
<tr>
<td>7 Petal bend with $r^2$ deviation</td>
<td>5 cm</td>
<td></td>
</tr>
<tr>
<td>Out of plane petal bending, $r^2$ deviation</td>
<td>&gt;50 cm</td>
<td></td>
</tr>
<tr>
<td>8 The cross-track (telescope/occultor alignment)</td>
<td>75 cm</td>
<td></td>
</tr>
</tbody>
</table>

Contrast change below $10^{-12}$ at 0.6 micron
A simulated image of the solar system
Occulter Experiments

- Inside 40' x 8' x 4' enclosure to isolate from environment
- No optics between pinhole and mask
- No optics (currently) between mask and camera
- 4" diameter, occulter is inner 2"
- Etched from 400!m wafer at JPL
- Designed for $10^8$ contrast
First Results

Approximate locations shown in green on simulated image at right.

900s exposure, median intensity in box $4.9 \times 10^{-6}$

0.06s exposure, scaled to median intensity 1 in box
Telescope for Habitable Earths and Interstellar/Intergalactic Astronomy (THEIA)

PI: Jeremy Kasdin/David Spergel

Co-Investigators

Industry Partners: Lockheed Martin Missiles and Space, ITT Space Systems, LLC, Ball Aerospace
NASA Partners: Jet Propulsion Laboratory/Caltech, Goddard Space Flight Center, Ames Research Center, Marshall Space Flight Center

University Partners: Arizona State University, Caltech, Case Western Reserve University, University of Colorado, John Hopkins University, University of Massachusetts, University of Michigan, MIT, Penn State, Princeton University, Space Telescope Science Institute, University of California-Santa Barbara, University of California-Berkeley, University of Virginia, University of Wisconsin, Yale University
### Optimal designs for a 4 meter telescope

<table>
<thead>
<tr>
<th></th>
<th>1-dist. Occulter</th>
<th>2-dist. Occulter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occulter distance (km)</td>
<td>70400</td>
<td>55000</td>
</tr>
<tr>
<td>Occulter IWA (mas)</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Occulter spectral band (nm)</td>
<td>250-1000</td>
<td>250-700</td>
</tr>
<tr>
<td>Second occulter distance (km)</td>
<td>-</td>
<td>35000</td>
</tr>
<tr>
<td>Second occulter IWA (mas)</td>
<td>-</td>
<td>118</td>
</tr>
<tr>
<td>Second occulter spectral band (nm)</td>
<td>-</td>
<td>700-1000</td>
</tr>
<tr>
<td>Occulter radius (m)</td>
<td>25.6</td>
<td>20</td>
</tr>
<tr>
<td>Number of petals</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Petal length (m)</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Minimum gap between petals (mm)</td>
<td>0.12</td>
<td>1.0</td>
</tr>
<tr>
<td>Minimum width of petal tip (mm)</td>
<td>1.62</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*To scale:*

*Left: single distance occulter*

*Right: two-distance occulter*
Telescope Design

• Three Mirror Astigmat
• Baseline: MgF coatings on primary; LiF on secondary
• Pickoff mirror feeds general astrophysics instruments
• Exoplanet Characterizer;
• Star Formation Camera
• Ultraviolet Spectrograph
Stationkeeping using Pupil Sensor and Perfect Thrusters

- Full Nonlinear Dynamic Model
- Discrete Measurements and Kalman Filter for position information
- Continuous Thrusters plus noise
- Gravity gradient and solar pressure disturbances
- Feed forward control plus feedback linearization

Initial offset = 6.5 m
Initial state error = 10 m
• Geometric iwa given by size and distance of starshade (100 m at 100,000 km gives 100 mas).
• Full throughput outside geometric IWA.
• Throughput decays smoothly (& rapidly) inside geometric IWA.
• Unlimited outer working angle.
• Size increases with wavelength.
• Starshade must slew from target to target.
• Limited viewing angles due to Sun reflection off starshade.
• Challenging to manufacture and control
## Summary Comparison

<table>
<thead>
<tr>
<th>Internal Coronagraph</th>
<th>External Occulter</th>
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<tr>
<td>Variable Inner Working Angle</td>
<td>Fixed Inner Working Angle</td>
</tr>
<tr>
<td>Limited Outer Working Angle</td>
<td>Wide Outer Working Angle</td>
</tr>
<tr>
<td>Fixed, rapid repointing</td>
<td>Variable Slew Time</td>
</tr>
<tr>
<td>Large viewing angles</td>
<td>Small field of regard</td>
</tr>
<tr>
<td>Optics/Detector Limited Bandwidth</td>
<td>Variable BW (depends on size)</td>
</tr>
<tr>
<td>Relatively Low throughput</td>
<td>High throughput</td>
</tr>
<tr>
<td>Technology/Cost Drivers</td>
<td>Technology/Cost Drivers</td>
</tr>
<tr>
<td>• Off-axis, diffraction limited telescope</td>
<td>• Size &amp; Distance</td>
</tr>
<tr>
<td>• Telescope Stability</td>
<td>• Positioning Control &amp; Slewing</td>
</tr>
<tr>
<td>• Wavefront Control</td>
<td>• Manufacturing &amp; Deployment</td>
</tr>
<tr>
<td>• Small IWA Coronagraph (2 λ/D)</td>
<td>Accuracy</td>
</tr>
<tr>
<td></td>
<td>• Starshade Stability</td>
</tr>
</tbody>
</table>

**Notes:**
- Hybrid design was not tenable but complimentary suppression might make sense
- Premium placed on small/nearby starshade with small petals
  (lower mass, easier deployment, fits into fairing, lower fuel use, more rapid slews, easier to test, looser tolerances)
Performance Comparisons

Automated Monte Carlo Mission Generation

How many planets can a mission detect and characterize?
Completeness

A direct detection can be parametrized by two values:

- Difference in brightness between star and planet ($\Delta$mag)
- Angular separation between star and planet ($s$)

For detection, the angular separation must be greater than the instrument’s inner working angle (IWA) and the $\Delta$mag must be greater than the limiting $\Delta$mag.
For a given population of planets you can calculate the joint probability density function of $s$ and $\Delta\text{mag}$ (left image).

The cumulative distribution of this PDF tells you the probability of detecting a planet (given one exists) for a specified IWA and limiting $\Delta\text{mag}$ (right image) - this is the star's completeness.
4m Telescope

- Almost 40 Earthlike planets detected at eta = 1
- Small variations among approaches (except 3 λ/D coronagraph)
- 2 λ/D coronagraph gets more unique planets and about same number of spectra as MDO
- 3 λ/D coronagraph gets very few full spectra
8m Telescope

- Over 50 Earth-like planets detected at \( \eta = 1 \)
- Same thrusters as 4 m
- 3 \( \lambda/D \) still IWA limited, but better relative performance than 4 m
- For telescopes \( \geq 8 \) m, coronagraphs outperform occulters
Multiple Distance Occulters

- 4 and 8 m MDO have similar performance
- 16 m MDO has very poor performance compared to coronagraphs
- 1 m MDO does remarkably well (25 Earthlike planets at $\eta = 1$). May be a good choice for a lower cost (probe) mission. Only way to get Earths at this scale.
How Optimistic is Coronagraph Result?

- Small variations for wide range of coronagraph throughputs
- Assumes long integration times are viable

Unique Planet Detections

Spectral Characterizations between 250 and 1000nm

Thursday, November 12, 2009
**Summary**

<table>
<thead>
<tr>
<th>Unique Detections</th>
<th>2 $\lambda/D$</th>
<th>3 $\lambda/D$</th>
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<tbody>
<tr>
<td>SDO 1 m</td>
<td>X</td>
<td>X</td>
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<tr>
<td>MDO 1 m</td>
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<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>SDO 4 m</td>
<td>X</td>
<td>31</td>
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<tr>
<td>MDO 4 m</td>
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<td>32</td>
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<tr>
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<td>54</td>
<td>54</td>
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<td>MDO 16 m</td>
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<td>102</td>
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Full Spectra

<table>
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<th>2 $\lambda/D$</th>
<th>3 $\lambda/D$</th>
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</thead>
<tbody>
<tr>
<td>SDO 1 m</td>
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<tr>
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<tr>
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<tr>
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<tr>
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</tbody>
</table>

$\eta_{Earth} = 1$

- At 4 m, little difference among architectures (except 3 $\lambda/D$ coronagraph) with some optimism
- Choice driven by technology and cost
- 1 m & 4 m MDO get similar numbers of detections!
- Starshades offer diminishing returns above 8 m without significant improvements in thrust/Isp

Thursday, November 12, 2009
Are there less expensive options we can do sooner?

Can they get Earths?
JWST + Occulter

• Remi Soummer, Web Cash, et al.

• Advantages:
  – JWST will soon launch
  – 6 meter telescope
  – NirSpec

• Disadvantages:
  – Diffraction limited at 2 microns
  – Limited telescope time
  – Requires adding new filters
  – Requires very large tilted occulter (>60 m tip-to-tip) to increase operating angles
  – Occulter must do acquisition and control as well as move to targets.
  – Complexities of interfacing with major mission
Moderate Telescope + Occulter

- 1.1 -1.5 meter telescope (diffraction limited at 0.3 - 0.5 microns)
- Advantages:
  - Lightweight relatively inexpensive telescope can move, acquire occulter
  - Same resolving power as JWST
  - Can use smaller occulter (< 30 m) with relaxed requirements.
  - Can detect up to 5 Earths with eta = 0.3
  - Can repeat visits for orbits
  - Can detect ozone
  - Opportunities for general astrophysics
Thank You.