

# HIGH CONTRAST IMAGING WITH BAND LIMITED MASK TECHNOLOGIES



Dr. Joseph Carson  
NASA Postdoctoral Program Fellow  
Jet Propulsion Laboratory

# COLLABORATORS

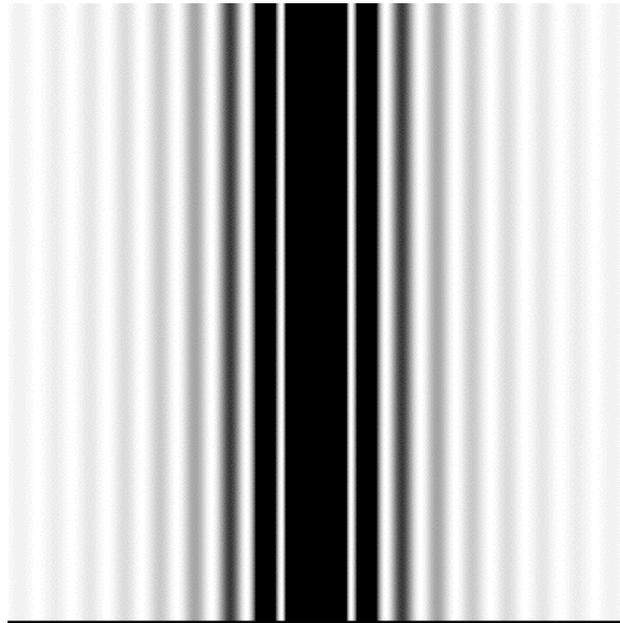
- Justin Crepp (Univ Florida)
  - Gene Serabyn (JPL)
  - Jian Ge (Univ Florida)
  - Karl Stapelfeldt (JPL)

# CONVENTIONAL CORONAGRAPHIC IMAGING MASKS

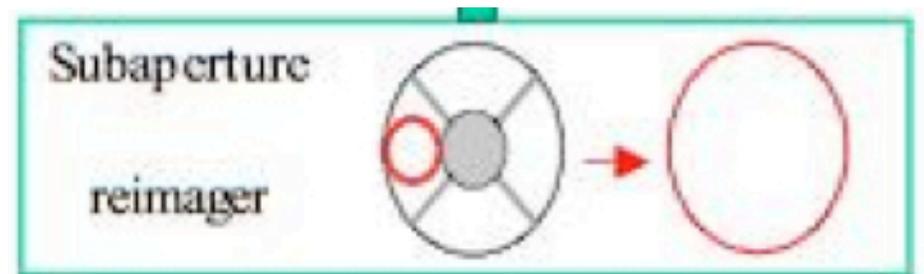
HIP 73470  
Separation  $\sim 0.9''$   
Differential Mag  $\sim 3.5$



# Our Strategy: A band-limited focal plane mask implemented on a Palomar Off-Axis Subaperture



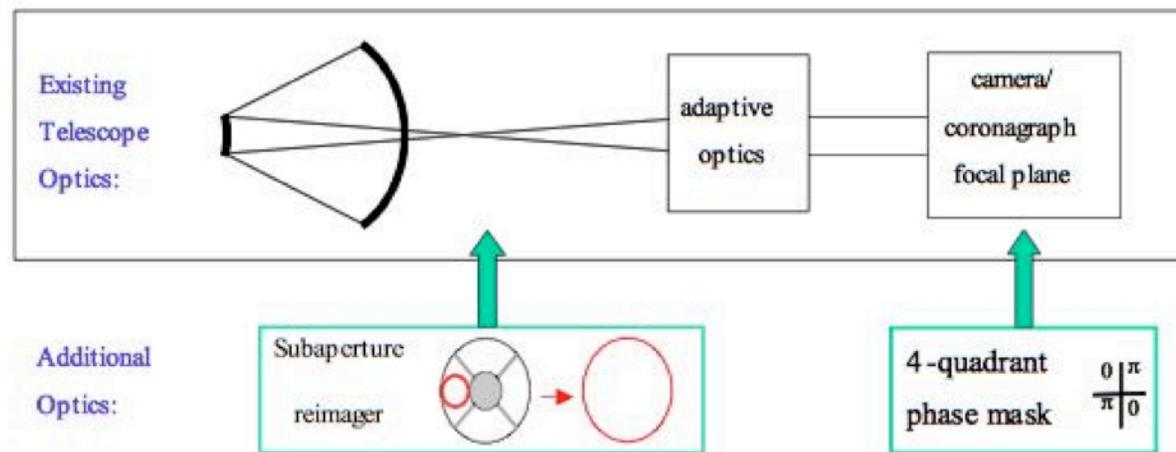
Band Limited Mask



Off-Axis Subaperture Reimager

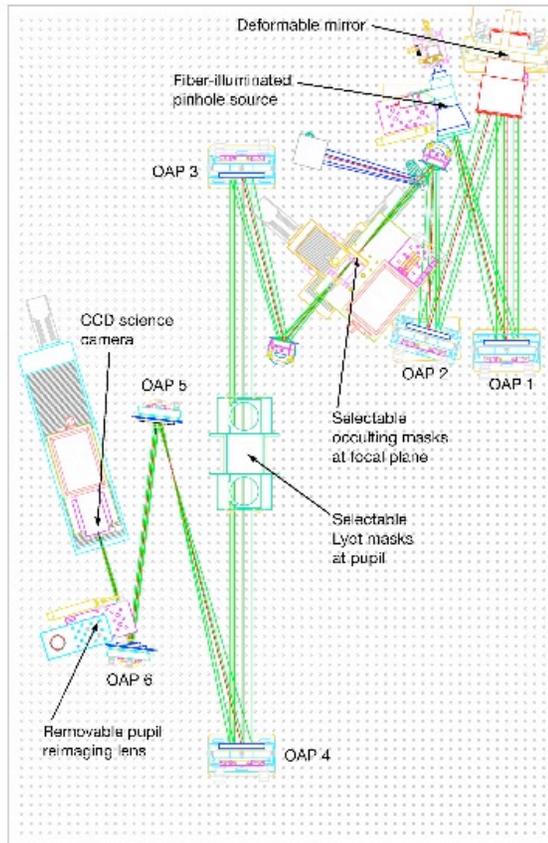
# Our Observing Platform

## A 1.5 meter Off-Axis Subaperture Imaging Capability on the Palomar Hale Telescope



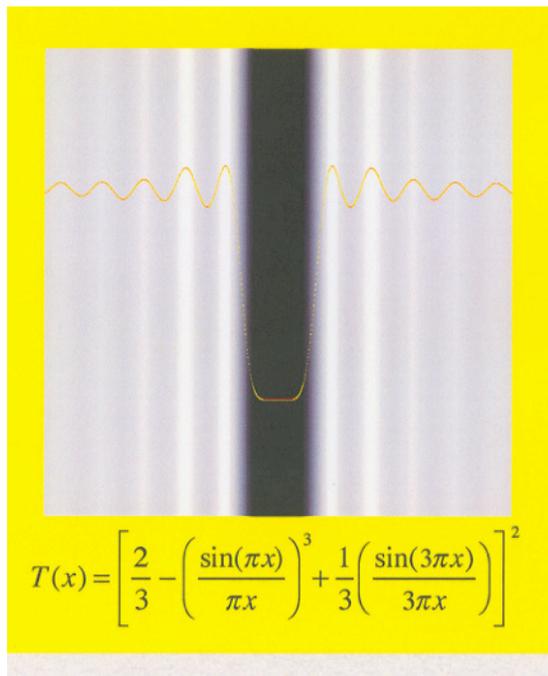
Haguenauer et al. 2005

# The JPL High Contrast Imaging Testbed (HCIT)

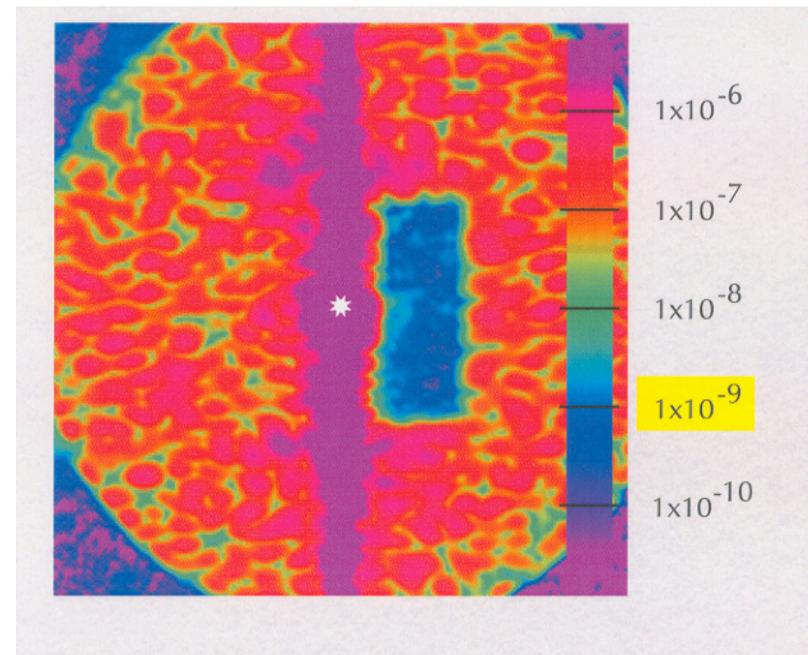


Trauger et al. 2004

# HCIT Coronagraphy

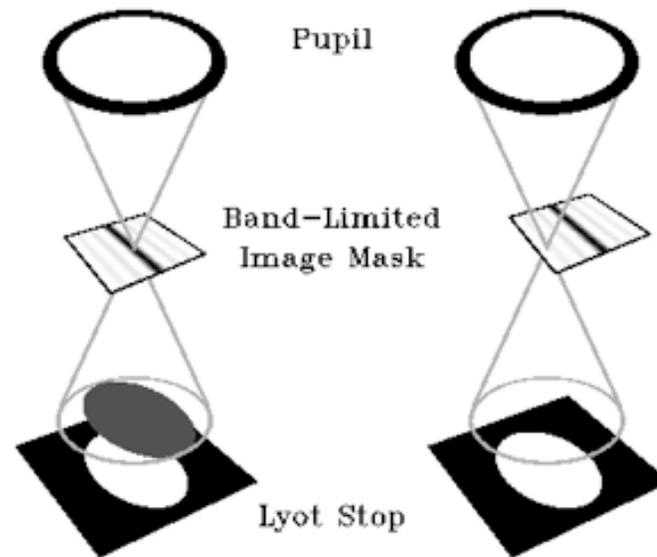


Band Limited Mask



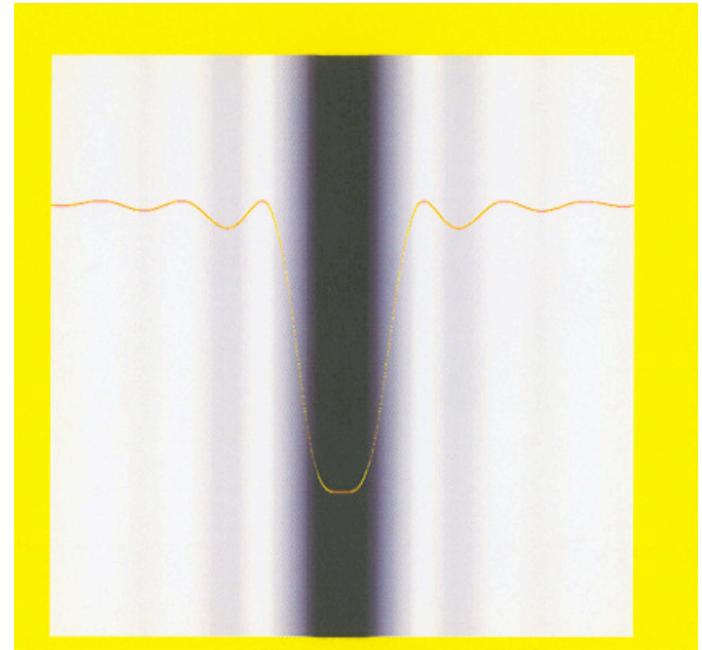
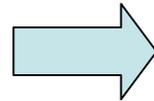
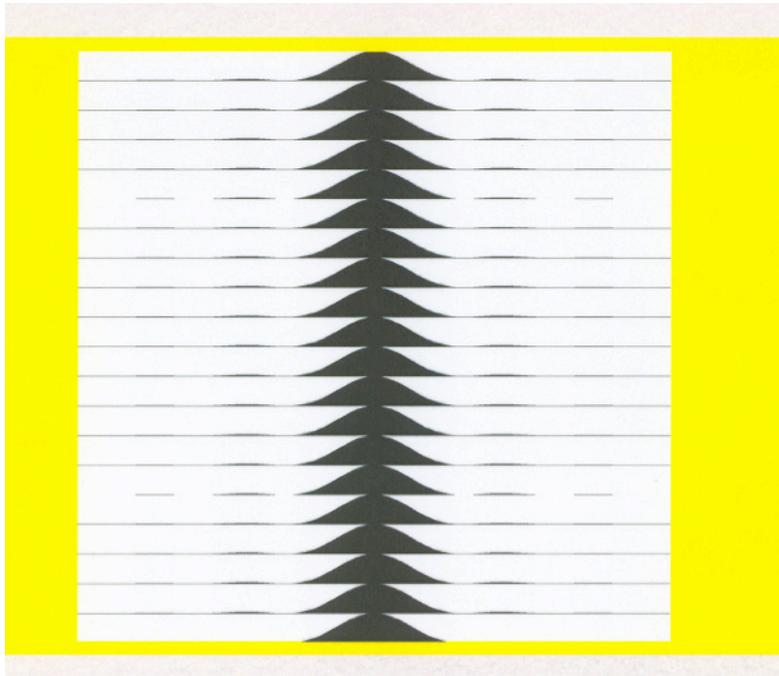
$10^{-9}$  Contrast at  $4\lambda/D$   
(laser light)

# Band-Limited Mask

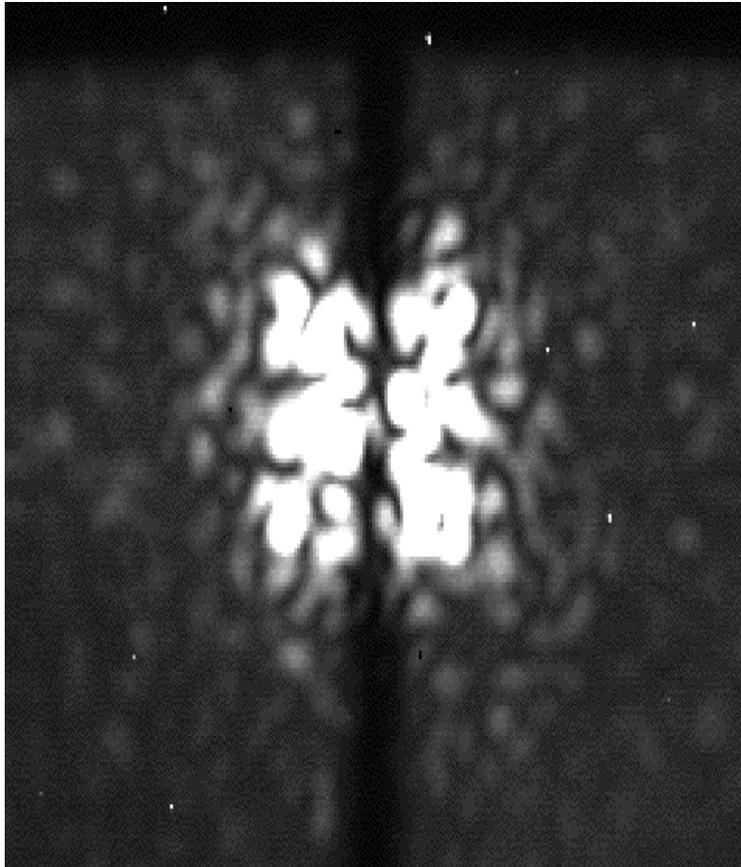


This figure illustrates schematically how a coronagraph works: light passes through the pupil and converges on an image mask, then the pupil is imaged onto a Lyot stop. Starlight focused on the center of the image mask diffracts to the pupil edges, where the Lyot stop can block it, as shown on the left of the figure. Light from an off-axis planet diffracts all around the second pupil plane, as shown on the right of the figure, and largely passes through the Lyot stop.

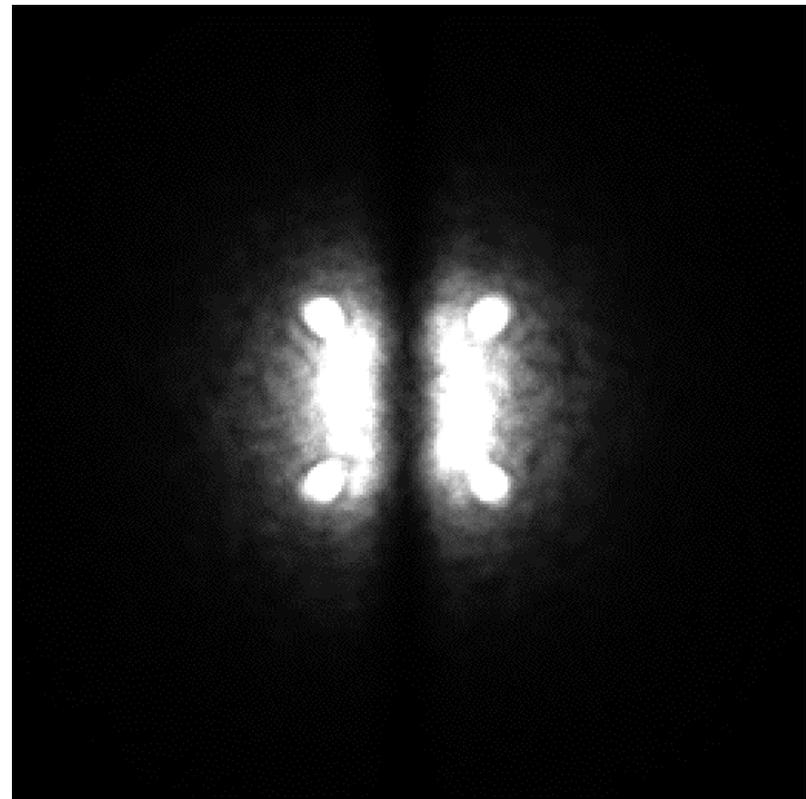
# A Binary “Half-Tone” Band-Limited Mask



# CORONAGRAPHED AO WHITE LIGHT

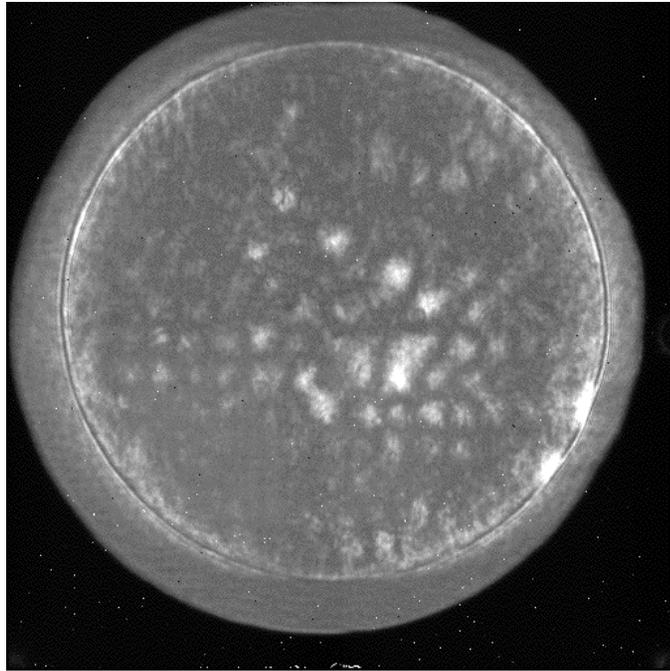


EXPERIMENTAL

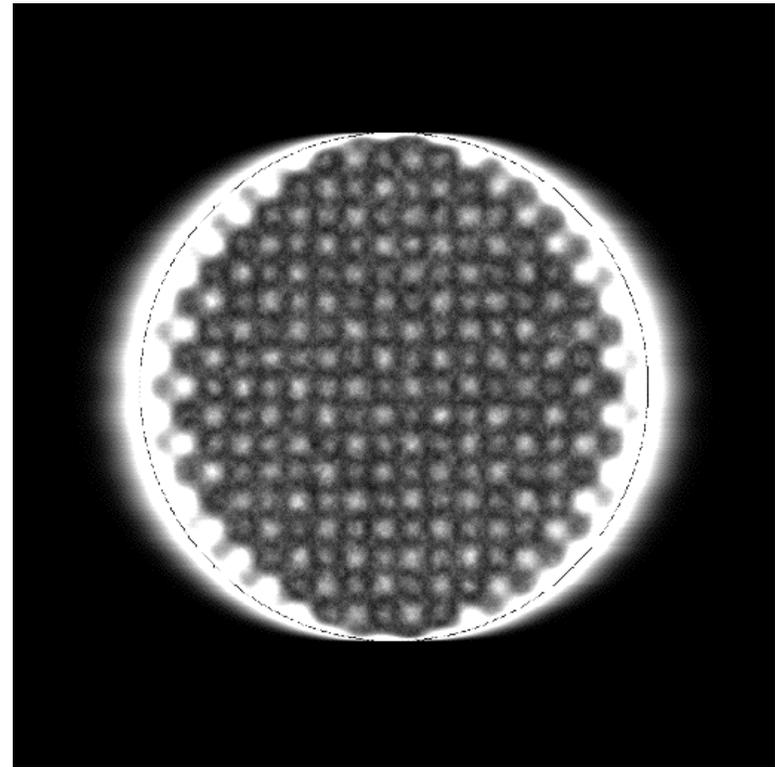


SIMULATED

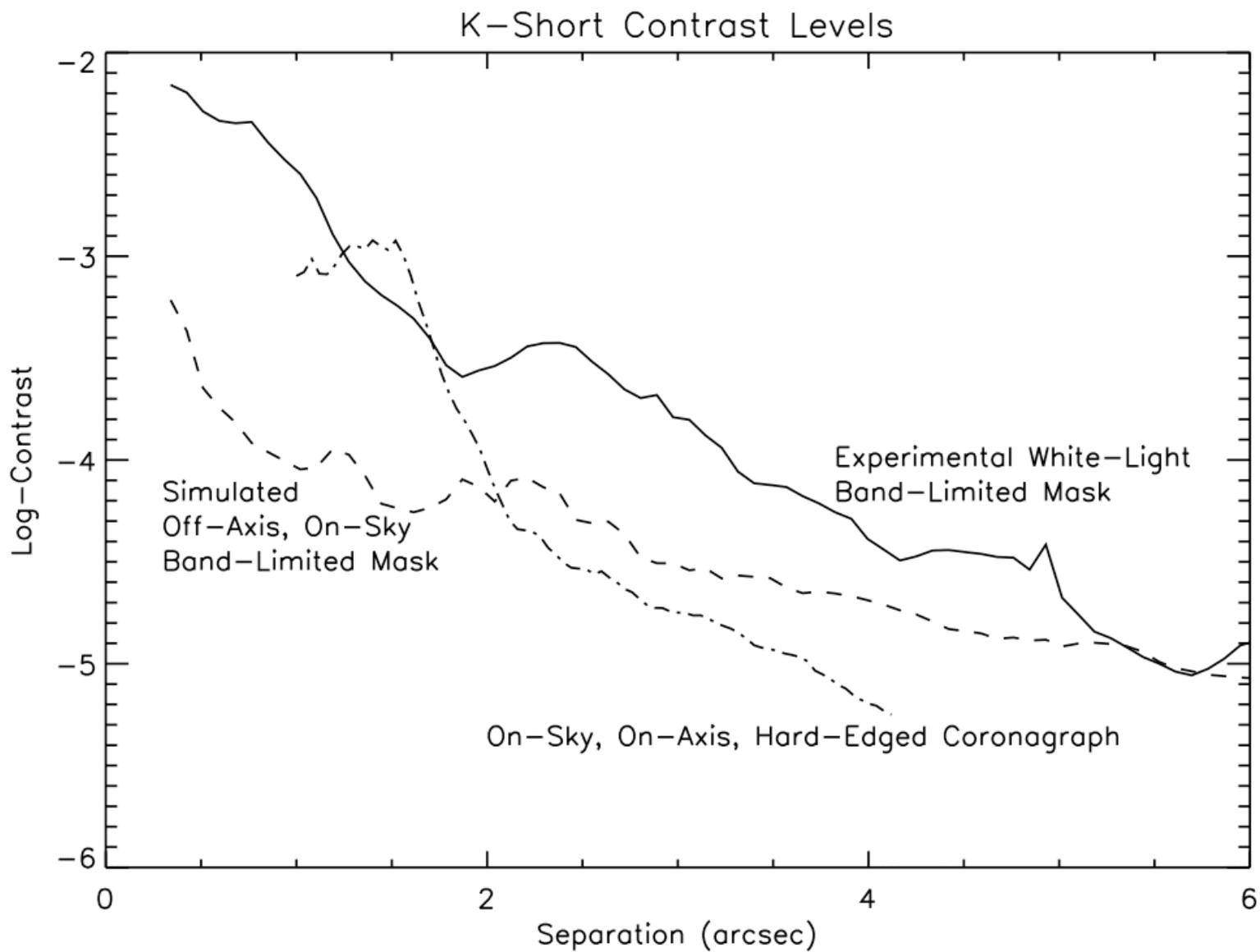
# Pupil Image



Experimental



Simulation



# Summary

- We implemented a binary version of a band limited mask for use with the Palomar Hale Telescope Adaptive Optics System.
- Preliminary instrument tests suggest we currently achieve only marginal improvement over hard-edged spot coronagraphy.
- We believe that we are limited by the AO wavefront performance.

# Acknowledgments

- We thank the Palomar Observatory staff for their invaluable support with instrument testing.
- We thank the 4QPM group for their accommodation of our hardware and testing.
- We thank the JPL AO group for their guidance and advice for mask design and testing.
- We thank the JPL Innovative Spontaneous Concepts program for its support of this project.

# A Palomar Adaptive Optics Coronagraphic Survey of TPF-C Candidate Targets



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Jet Propulsion Laboratory



Alex Rudolph, California State Polytechnic University, Pomona

We present here a status report on an ongoing Palomar Hale Telescope adaptive optics coronagraphic survey that searches for sub-stellar companions around 28 TPF-C candidate targets. Sub-stellar objects found around such targets could have important implications for space-based observing programs like TPF-C, that wish to image narrow-separation planetary objects; an existent brown dwarf companion, for instance, might degrade the sensitivity of narrow-separation space-based observations by way of its interfering light; or, the existence of an orbiting brown dwarf could affect the likelihood of a narrow-separation planetary orbit. Our survey therefore helps constrain and direct TPF-C candidate target selection, while providing scientifically important substellar companion information on the nearby stellar neighborhood.

## Targets



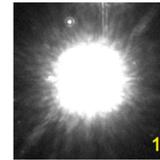
For our target list, we select the nearby ( $d < 20\text{pc}$ ) FGK dwarfs that have been proposed as targets for NASA's Terrestrial Planet Finder Coronagraph (TPF-C) mission. We reviewed the top 100 targets for TPF-C and removed targets that had previously been observed by other programs such as ongoing SIM reconnaissance observations being conducted at Palomar. Our final target list, shown on the right, includes a median target distance of 16.9 parsecs, and a median spectral type of G3V.

Object	RA	Dec	Remarks
HP6379	01 21 59.12	76 42 37.02	V=7.17
HP13402	02 52 32.13	-12 46 10.97	V=6.05
HP18859	04 02 36.75	-00 16 08.12	V=5.38
HP27435	05 48 34.94	04 05 40.73	V=5.97
HP28954	06 06 40.48	15 32 31.36	V=6.76
HP29525	06 13 12.50	10 37 37.72	V=6.43
HP32439	06 46 14.15	79 33 53.32	V=5.44
HP34017	07 03 30.46	29 20 13.49	V=5.93
HP35136	07 15 50.14	47 14 23.87	V=5.54
HP38784	07 56 17.23	80 15 55.95	V=6.55
HP39157	08 00 32.13	29 12 44.48	V=6.97
HP40693	08 18 23.95	-12 37 55.82	V=5.95
HP40843	08 20 03.86	27 13 03.74	V=5.13
HP42438	08 39 11.70	65 01 15.26	V=5.63
HP44897	09 08 51.07	33 52 55.98	V=5.95
HP49081	10 01 00.66	31 55 25.22	V=5.37
HP53721	10 59 27.97	40 25 48.92	V=5.03
HP62207	12 44 59.41	39 16 44.10	V=5.95
HP70319	14 23 15.29	01 14 29.65	V=6.25
HP72367	14 50 15.81	23 54 42.64	V=5.86
HP73775	16 04 56.79	39 09 23.43	V=6.66
HP79248	16 10 24.31	43 49 03.52	V=6.61
HP82588	16 52 58.80	-00 01 35.12	V=6.65
HP83389	17 02 36.40	47 04 54.77	V=6.76
HP95319	19 23 34.01	33 13 19.08	V=6.37
HP98792	20 03 53.13	23 20 26.47	V=7.28
HP100017	20 17 31.33	66 51 13.27	V=5.91
HP116085	23 31 22.21	59 09 55.86	V=6.76

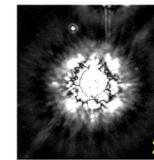
## Data Reduction

Our data reduction begins with standard reduction procedures including sky-subtraction, flat-fielding, bad-pixel correction, and median-combination of individual frames. Next we apply a Fourier-filter, which filters out low-frequency spatial features such as internal instrument reflection ghosts. We next use our software to rotate the frame and subtract it from itself. Finally, we inspect Fourier-filtered, non-Fourier-filtered, rotationally-subtracted, and non-rotationally-subtracted frames to identify potential companions.

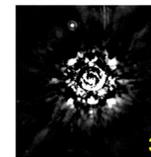
Median-Combined, Sky-Subtracted, Flatfielded, Coronagraphic Image



Fourier-Filtered Version

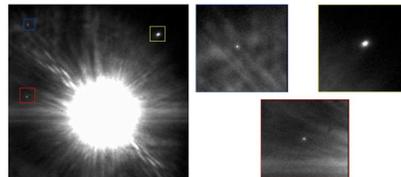


Rotated and Subtracted Version



## Observing Procedures

We utilize the Palomar Hale Telescope Adaptive Optics (AO) System to achieve diffraction-limited resolutions at K-band (2.2-micron) for a 5-meter primary mirror aperture. We combine the AO system capabilities, with strehl ratios typically 30-70%, with PHARO's 0.91-arcsecond coronagraphic spot, to help suppress the light from the parent star and resolve faint objects nearby.



Above: Three objects can easily be seen in the field near the target star. These objects are at angular separations of 13.8, 11.3, 9.2 arcseconds clockwise from top left, which correspond to physical separations of 214, 175 and 142 AU. If they are indeed companions. Follow up observations are needed to check for companion status, as well as brown dwarf status.

## Future Work

We are currently on schedule to complete the observing phase of the survey by December 2006. During our concluding observations, we expect to observe candidate companions for common proper motion, and complete reconnaissance of remaining new targets.

In parallel with this observing effort, we have developed Monte Carlo population simulations to derive the true companion fraction from the observed result. This phase is crucial to deriving accurate companion statistics since observational results may be biased by factors such as orbital projection effects. We expect to use our Monte Carlo simulations to combine these observational results with other surveys to conclude accurate population statistics.

## Acknowledgements

We thank the Palomar Observatory staff for their support of these observations. K. Hiner was supported in part by the Kaye Reeder Scholarship at Cal Poly Pomona. The research conducted by J. Carson and K. Stapelfeldt, and part of the research conducted by K. Hiner, was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Association.

The Cornell High-order Adaptive Optics Survey for Brown  
Dwarfs in Stellar Systems–II: Results from Monte Carlo  
Population Analyses

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**ABSTRACT**

In this second of a two-paper sequence, we present Monte Carlo population simulation results of brown dwarf companion data collected during the Cornell High-order Adaptive Optics Survey for brown dwarf companions (CHAOS). Making reasonable assumptions of orbital parameters (random inclination, random eccentricity and random longitude of pericentre) and age distributions, and using published mass functions, we find that the brown dwarf companion fraction around main sequence stars is 0.0%–9.3% for the 25–100 AU semi-major axis region. We find a corresponding L-dwarf companion fraction of 0.0%–3.3%. We compare our population analysis methods and results with techniques and results presented by several other groups. In this comparison we discover that systematic errors (most notably resulting from orbital projection effects) occur in the majority of previously published brown dwarf companion population estimates, leading authors to claim results not supported by the observational data.

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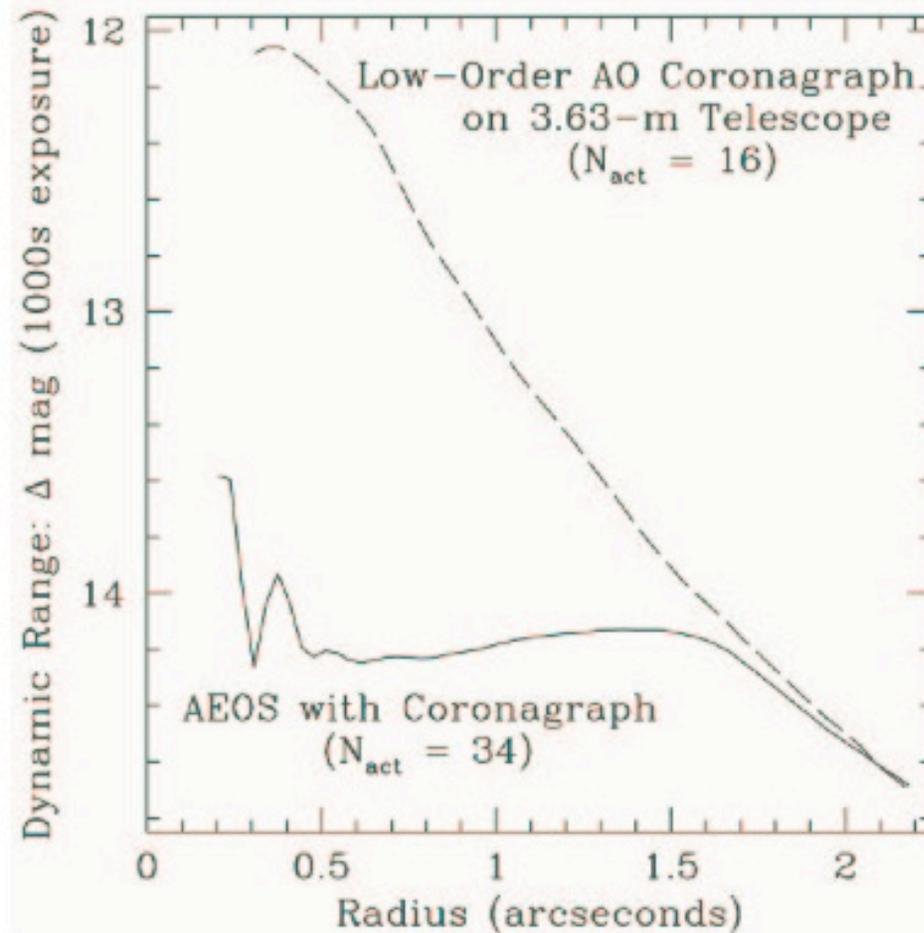
## Other Operational High Contrast Systems

- Lyot Project



US Airforce AEOS Telescope on Haleakala

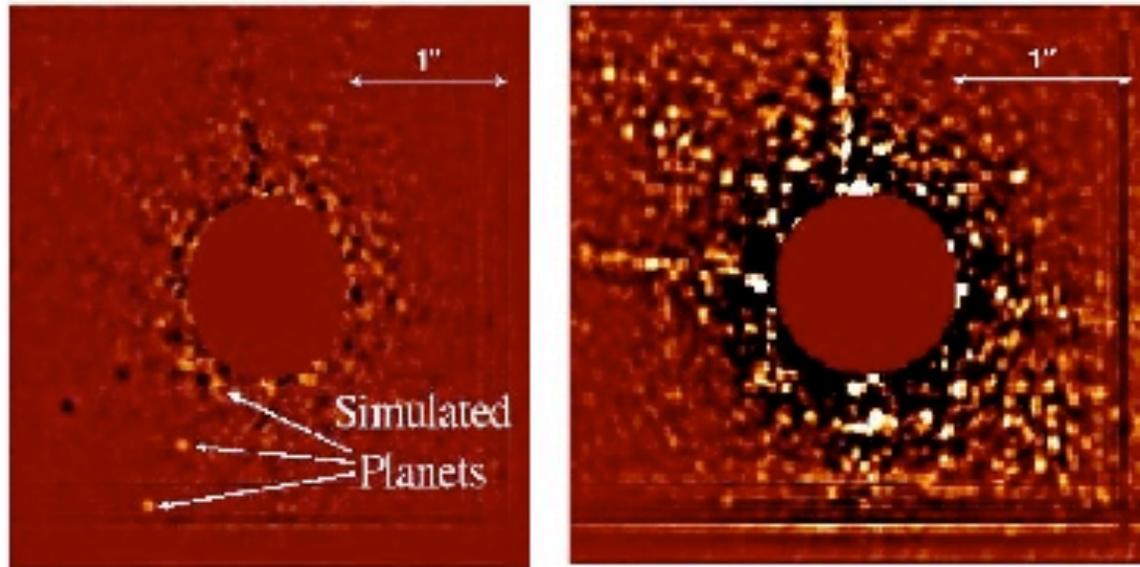
## Other Operational High Contrast Systems



Dynamic range for a 1000 s exposure with the AEOS coronagraph

## Other Operational High Contrast Systems

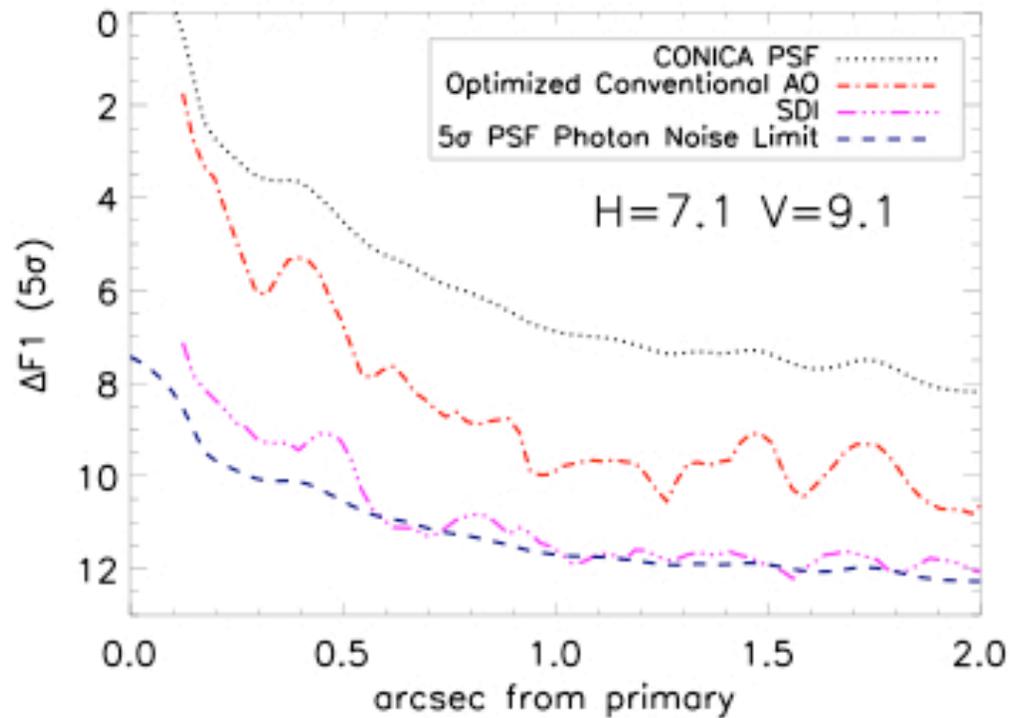
- Simultaneous Differential Imager on VLT NACO



Biller et al. 2005

## Other Operational High Contrast Systems

- Simultaneous Differential Imager on VLT NACOS



# Advantages of our 1.5-meter Subaperture Setup

- Adaptive Optics system achieves better wavefront control, compared to a full aperture setup. (Subaperture Strehl ratios = 90%-95%.)
- No Secondary Mirror or Spider Support Obscurations.

# Palomar Band-Limited Mask Tested In-Lab

**HIGH CONTRAST IMAGING WITH THE HALE 200" TELESCOPE AT PALOMAR**  
 Justin Crepp<sup>1</sup>, Joseph Carson<sup>2</sup>, Eugene Serabyn<sup>2</sup>, Jian Ge<sup>1</sup>, Ivan Kravchenko<sup>1</sup>, Andrew Vanden Heuvel, & Shane Miller  
<sup>1</sup> University of Florida, Gainesville, FL; <sup>2</sup> Jet Propulsion Laboratory, Pasadena, CA

**Abstract:**

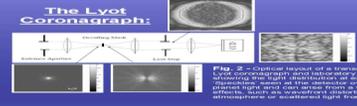
We present recent work on a high-contrast imaging effort designed to search for Earth-like exoplanets with existing observatory assets. Our strategy is to use the Palomar 200" telescope at Hale Observing Station in California to observe a large number of stars in the range of 10 to 100 parsecs. We will use a Lyot coronagraph to suppress the light from the star and a band-limited mask to suppress the light from the atmosphere and scattered light from the optics. We will use a coronagraph to suppress the light from the star and a band-limited mask to suppress the light from the atmosphere and scattered light from the optics.

**High Strehl Ratios:**



**Fig. 1** - Images of a coronagraph mask with a central hole and a band-limited mask with a central hole.

**The Lyot Coronagraph:**



**Fig. 2** - Optical layout of a Lyot coronagraph showing the star, Lyot stop, and mask.

**Fig. 3** - Binary band-limited image masks manufactured with nanoscale precision and 2 micron outer diameter. The outer-to-outer distance of each mask is less than 5 X 70.

**Prototype Designs:**



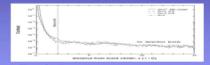
**Fig. 4** - Image of a prototype mask (top-left) and Lyot stop (top-right) for the mask in Figure 1 (right).

**Fig. 5** - Electron beam lithography mask used at the University of Florida and Jet Propulsion Laboratory in the mask fabrication process.

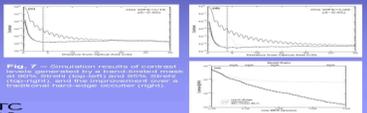
**Department of Astronomy**  
 211 Bryant Space Science Center  
 PO Box 112055  
 Gainesville, FL 32611-2052

Contact: jcrepp@astro.ufl.edu

**Anticipated Performance:**



**Fig. 6** - Comparison of the on-axis intensity of the Lyot stop and the mask shown in Fig. 1 - center-right.



**Fig. 7** - Simulation results of coronagraph performance. Left: Contrast vs. radius. Right: Contrast vs. radius for a band-limited mask (top) and a Lyot stop (bottom).

**First Light Science with the GTC**  
 Miami, FL, US, June 28-30, 2006

# Palomar Band-Limited Mask Tested In-Lab

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<sup>1</sup> University of Florida, Gainesville, FL; <sup>2</sup> Jet Propulsion Laboratory, Pasadena, CA



### Abstract:

We present recent work on a high-contrast imaging effort designed to search for sub-stellar companions orbiting nearby stars. Our strategy is to use the high-Strehl off-axis reimager at the Hale 200" at Palomar in combination with a Lyot coronagraph that is equipped with a band-limited image mask. In principle, this architecture can generate contrast levels on the order of  $10^{-5}$  at angular separations  $> 900$  mas from the star in the near-infrared. We are on schedule to perform daytime white light tests in August, and hope to demonstrate this technology on the sky in the Fall. Currently, this level of contrast has only been achieved over a very narrow bandwidth in the southern hemisphere using the VLT. With our anticipated sensitivities, brown-dwarfs and young large-separation Jovian planets can be imaged.

### High Strehl Ratios:

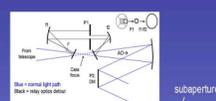


Fig. 1 - Strehl ratios exceeding 90% at near-infrared wavelengths have been achieved using a clever optical scheme that effectively turns the Hale 200" (5.093 m) telescope into a smaller (1.5 m) off-axis imager (Serabyn et al. 2005, 2006). To eliminate unwanted diffraction, the subsequent circular subaperture conveniently avoids the telescope central obstruction and spiders, and is then magnified and reimaged via relay optics onto the AO system deformable mirror.

### The Lyot Coronagraph:

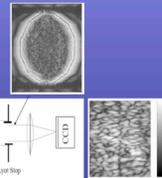
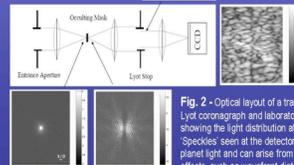


Fig. 2 - Optical layout of a transmissive Lyot coronagraph and laboratory images showing the light distribution at each location. Spokes seen at the detector overwhelm planet light and can arise from a variety of effects, such as wavefront distortions from the atmosphere or scattered light from the optics.



Fig. 3 - Binary band-limited image masks manufactured with nanoscale precision using electron-beam lithography. The inner-working-distance of each mask is less than  $3 \lambda / D$ .

### Prototype Designs:

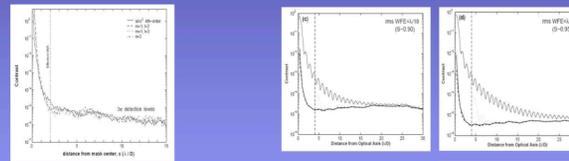


Fig. 5 - Electron-beam lithography instrument at the University of Florida (left) and Ivan Kravchenko working in the class 100 clean-room (above).

Fig. 6 - Image of a prototype mask (bottom-left), optical microscope image of the mask's detailed structure (bottom-right), and Aluminum holder for the mask in PHARO (right).



### Anticipated Performance:



# Band-Limited Mask Simulated On-Telescope Performance

## HIGH CONTRAST IMAGING WITH THE HALE 200" TELESCOPE AT PALOMAR

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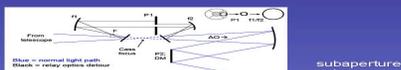
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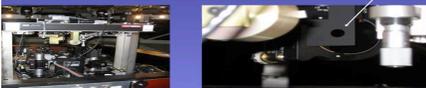
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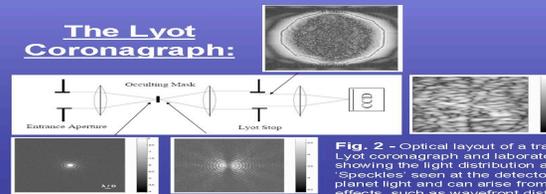


subaperture



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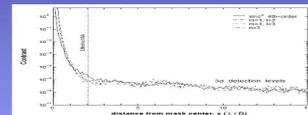
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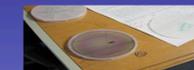


### Prototype Designs:

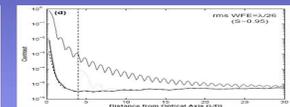
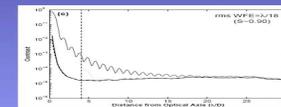


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**Fig. 6** - Image of a prototype mask (bottom-left), optical microscope image of the mask's detailed structure (bottom-right), and Aluminum holder for the mask in PHARO (right).



### Anticipated Performance:



# Upcoming Schedule

- Mask calibration tests continue this Fall.
- Parallel development of a radial mask version using “sputter” fabrication techniques.
- On-sky calibration/science tests expected this winter..