Eclipse

A case study in high contrast coronagraphy for planet discovery: the concept and supporting laboratory experience

IAU Conference 200
Direct Imaging of Exoplanets: Science and Technology
Nice, France / 3-7 October 2005

Abstract

- Eclipse is a proposed NASA Discovery mission to perform a sensitive imaging survey of nearby planetary systems, including a survey for jovian-sized planets orbiting Sun-like stars to distances of 15 pc.
- We outline the science objectives of the Eclipse mission and review recent developments in the key enabling technologies.
- Eclipse is a space telescope concept for high-contrast visible-wavelength imaging and spectrophotometry. Its design incorporates a telescope with an unobscured aperture of 1.8 meters, a coronagraphic camera for suppression of diffracted light, and precise active wavefront correction for the suppression of scattered background light. For reference, Eclipse is designed to reduce the diffracted and scattered starlight between 0.33 and 1.5 arcseconds from the star by three orders of magnitude compared to any HST instrument.
- The Eclipse mission provides precursor science exploration and technology experience in support of NASA'a Terrestrial Planet Finder (TPF) program.

Investigation Team

John Trauger (JPL)
Robert A. Brown (STScI)
Michael Brown (Caltech)
Adam Burrows (U Arizona)
Chris Burrows (MetaJiva)
Mark Ealey (Xinetics)
Debra Fischer (SFSU)
Christ Ftaclas (U Hawaii IfA)
Sara Heap (GSFC)
Tony Hull (Tinsley)
Jeremy Kasdin (Princeton)
John Krist (JPL)
Marc Kuchner (GSFC)
Jonathan Lunine (U Arizona)
Geoff Marcy (UC Berkeley)
Raghvendra Sahai (JPL)
David Spergel (Princeton)
Karl Stapelfeldt (JPL)
Wesley Traub (JPL/SAO)
Bruce Woodgate (GSFC)

Engineering Partners

JPL
(Coronagraph Camera)

ITT Industries
Space Systems Division
(Optical Telescope Assembly)
Gary Matthews
Robert Egerman

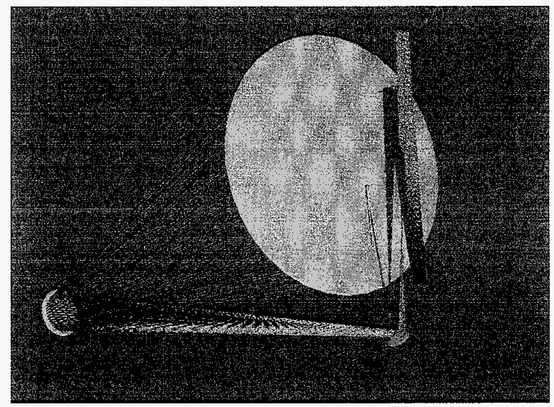
General Dynamics
Spectrum Astro Space Systems
(Spacecraft)
Chris Clark
John Dyster

Xinetics
(Active Optics)
Mark Ealey
Tom Price

Overview

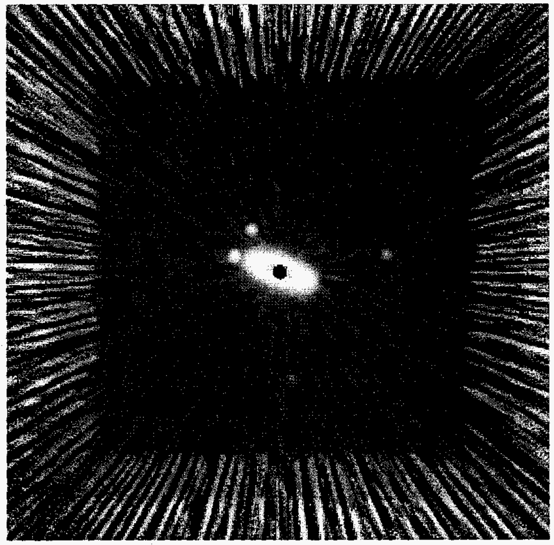
- The Eclipse concept
- Science case for Eclipse, including value as TPF precursor
- Baseline technology, requirements, development status
- Laboratory testbed for development and verification
- Predicted performance, based on models and current technology
- Conclusions

The Eclipse Mission Concept



- Unobscured off-axis telescope with 1.8 m diameter primary mirror
- High contrast coronagraphic camera with active wavefront correction
- Structural and thermal design for stable and precise optical alignment
- Emphasis on simplicity of design and minimum of optical elements
- Wavefront sensing at the science focal plane
- Earth-orbiting spacecraft for a 3+ year mission

Eclipse Science Objectives



Simulated composite image:
Altair (v=0.8 at 5.1pc)
Six-hour exposures in V, R, and I bands
Jupiters at 5, 10, and 20 AU
Brown dwarf at 40 AU
5-zodi disk
Field of view is 14 arcsec across.

- Spectrophotometry of known radial velocity planets.
- Survey for Jupiters (1 Mj mass, 5 Gyr age, 5 AU orbit) complete to S/N=10 for nearby stars to v=7 and 14 pc in multiple visits during a 3-year program (~100 stars).
- Sensitivity for EGPs and BDs orbiting beyond 5AU for stars beyond 14 pc (100s of candidate stars).
- Deeper exposures on interesting systems.
- Followup spectroscopy for planet characterizations.

Eclipse Science Objectives

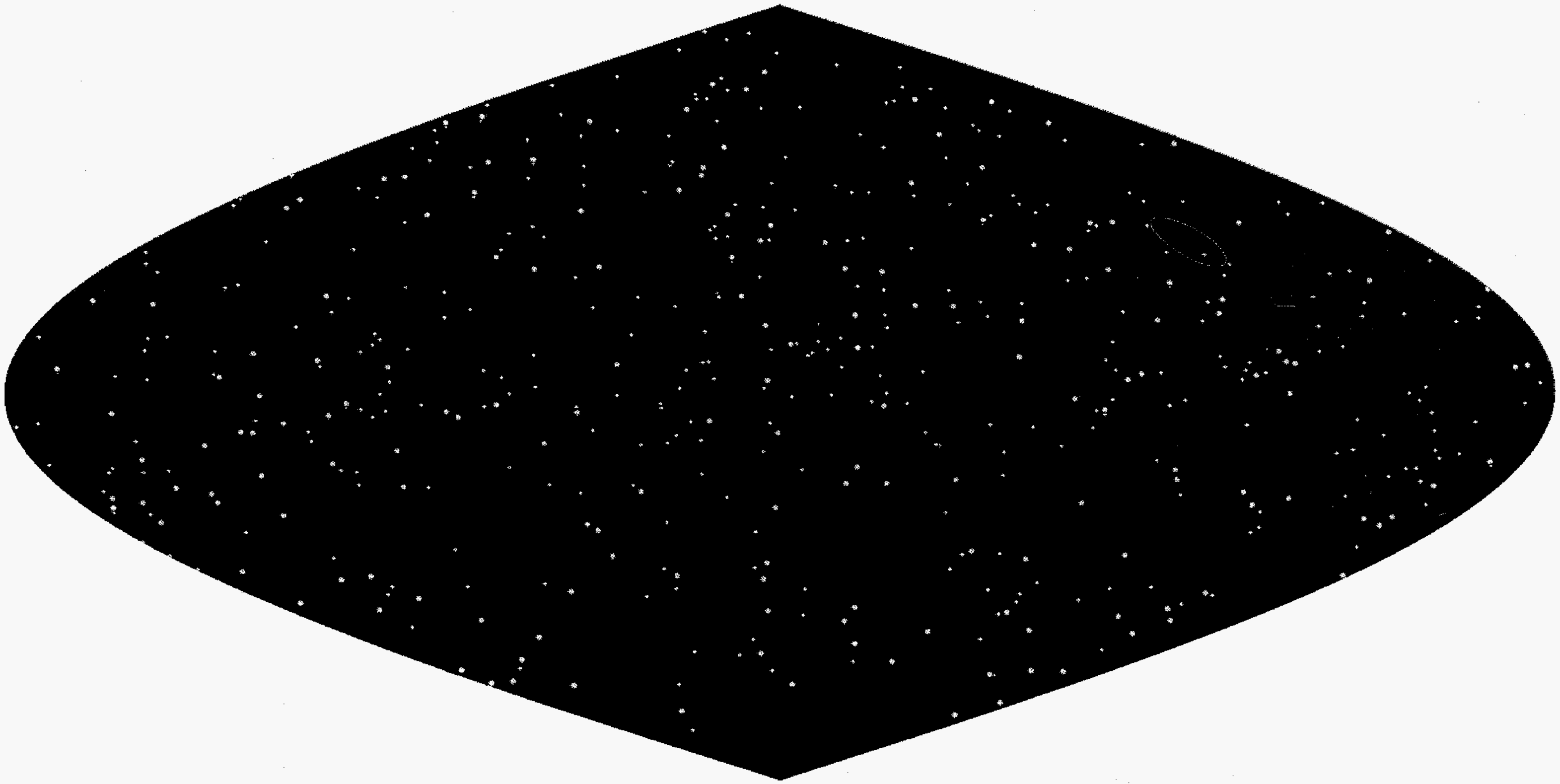
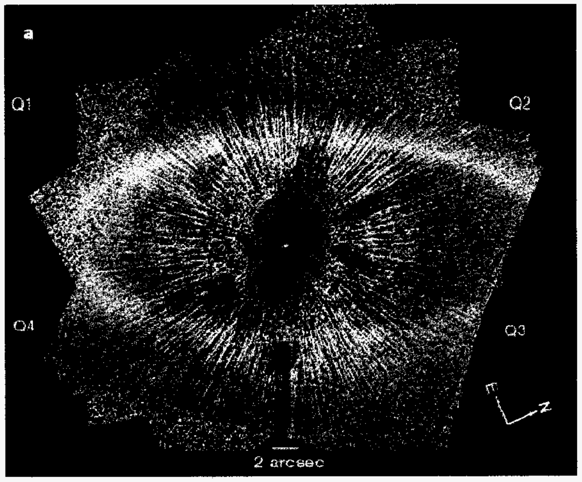


Chart of stars within 14 pc of the sun. The nearest stars will provide the first candidates for comprehensive exoplanetary missions such as TPF and Darwin.

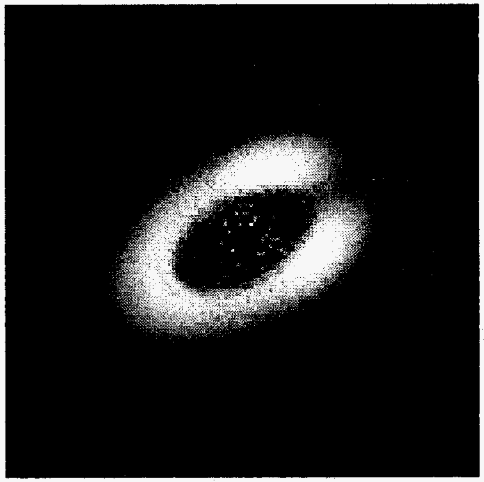
Chart shows: A-K stars (green), M stars (brown), and Kepler FOV (red circle).

Eclipse Science Objectives

- Imaging of circumstellar debris disks in reflected light.
- Debris disks can provide direct evidence of unseen planets.
- Sensitivity to 10 zodis in direct images.
- Will follow up on dozens of disks newly identified by Spitzer.



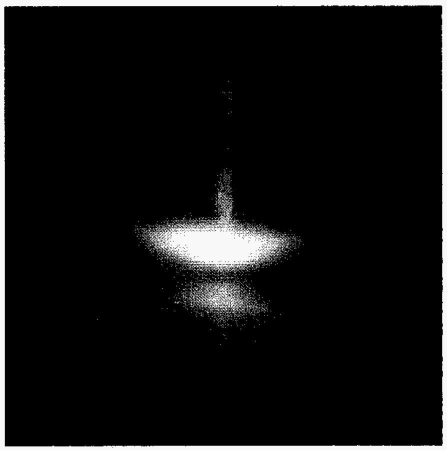
HST/ACS image of the dust ring orbiting Fomalhaut (Kalas et al 2005). Ring has an inner radius of 130 AU and width of 25 AU. The eccentric ring provides direct evidence of planetary perturbations.



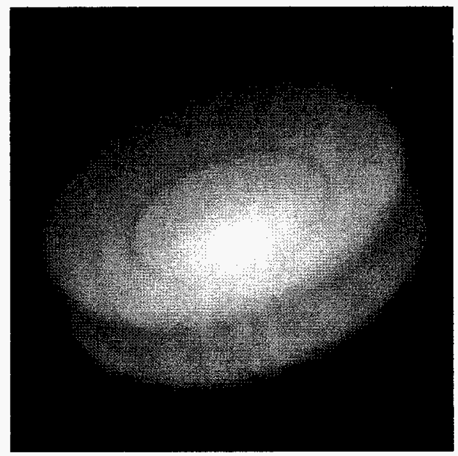
Simulated Eclipse image of a 10-zodi debris disk in reflected starlight (80 times fainter than Fomalhaut) for a debris disk at Neptune's orbit (35-65AU) with planet-induced dynamical structure.

Eclipse Science Objectives

- Circumstellar structure in Young Stellar Objects
- Structure of YSO disks evolves with the process of planet formation.
- Clearings and structure in the dust probes that evolution.

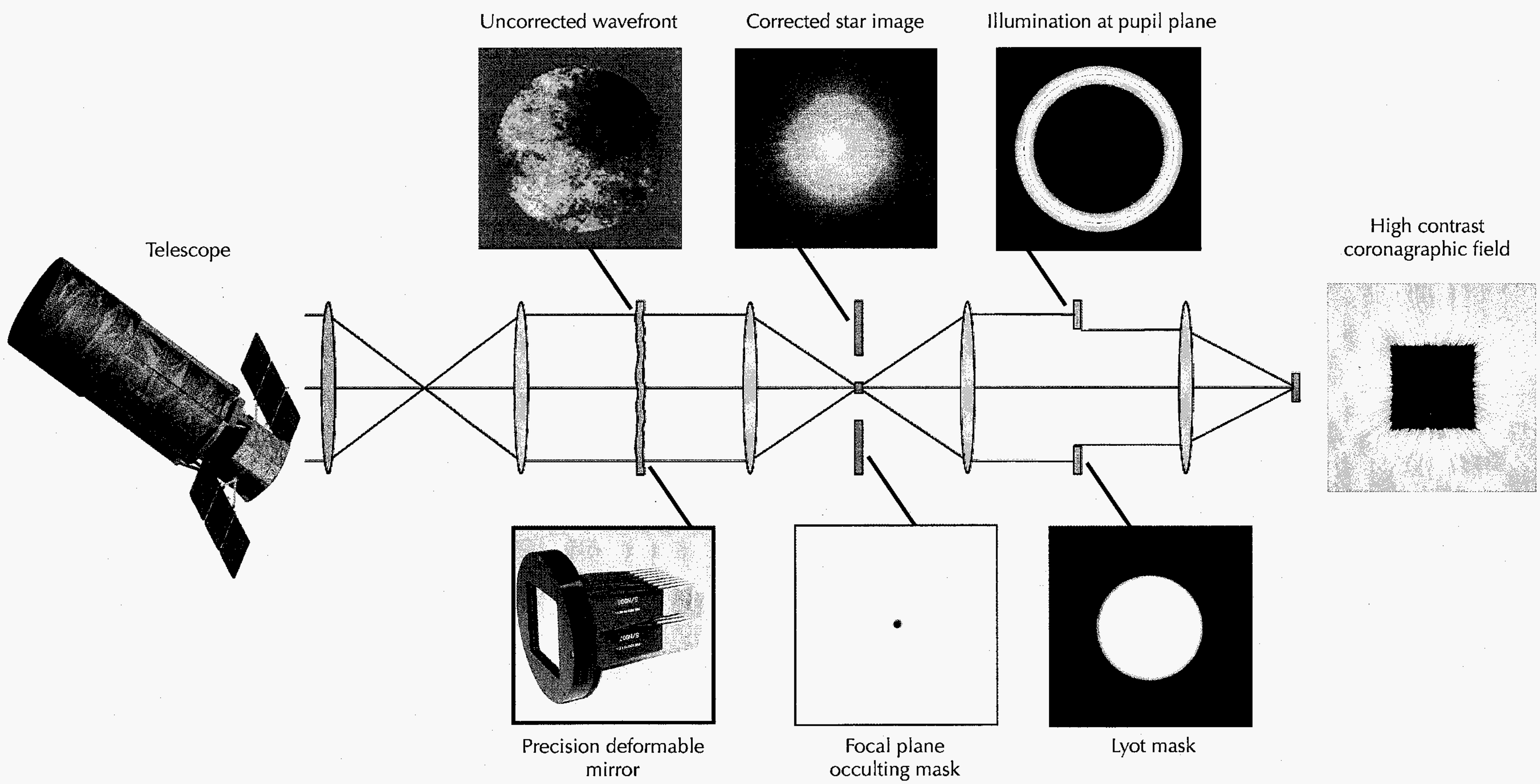


WFPC2/HST image of HH30 at 140 pc in visible light. Edge-on disk blocks the glare of the central star.

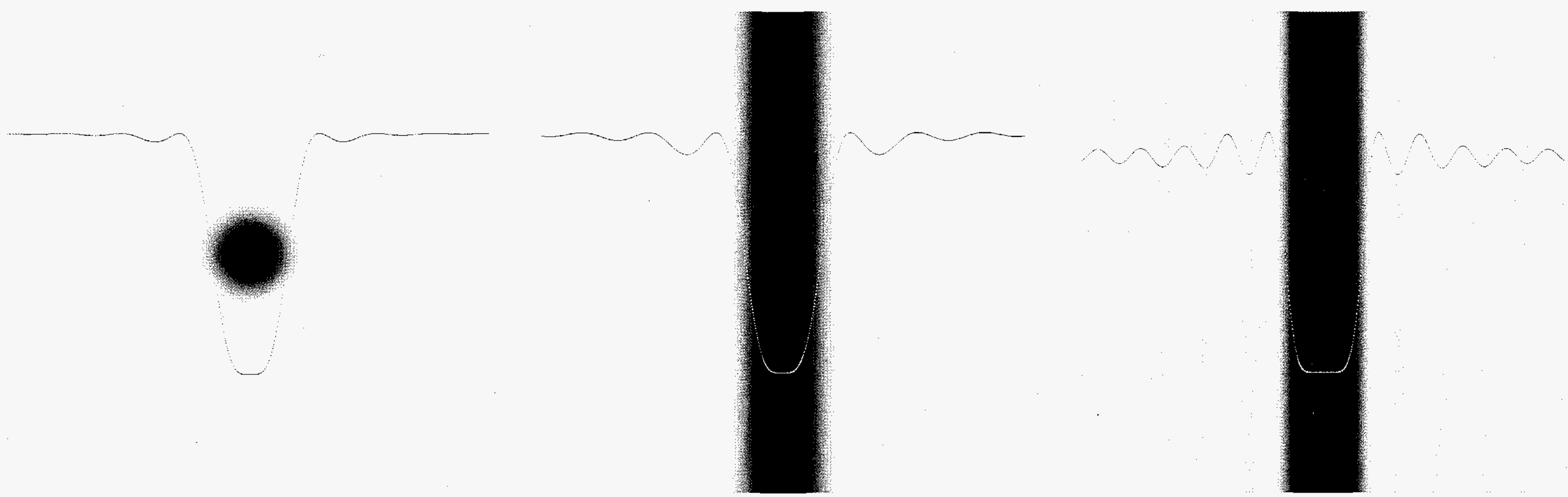


Simulated Eclipse image of a YSO disk with 10% the mass of HH30. The disk is inclined to the line of sight and central star is directly visible, but suppressed by the coronagraph.

Schematic diagram of the Eclipse coronagraph



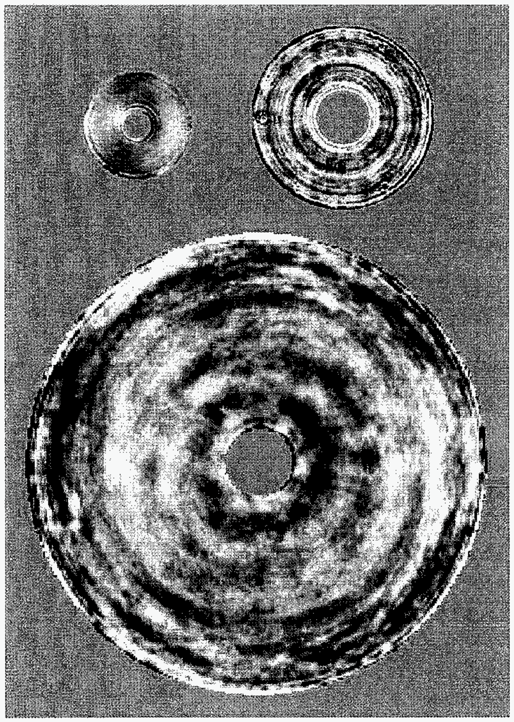
Eclipse implements selectable focal plane occulting masks

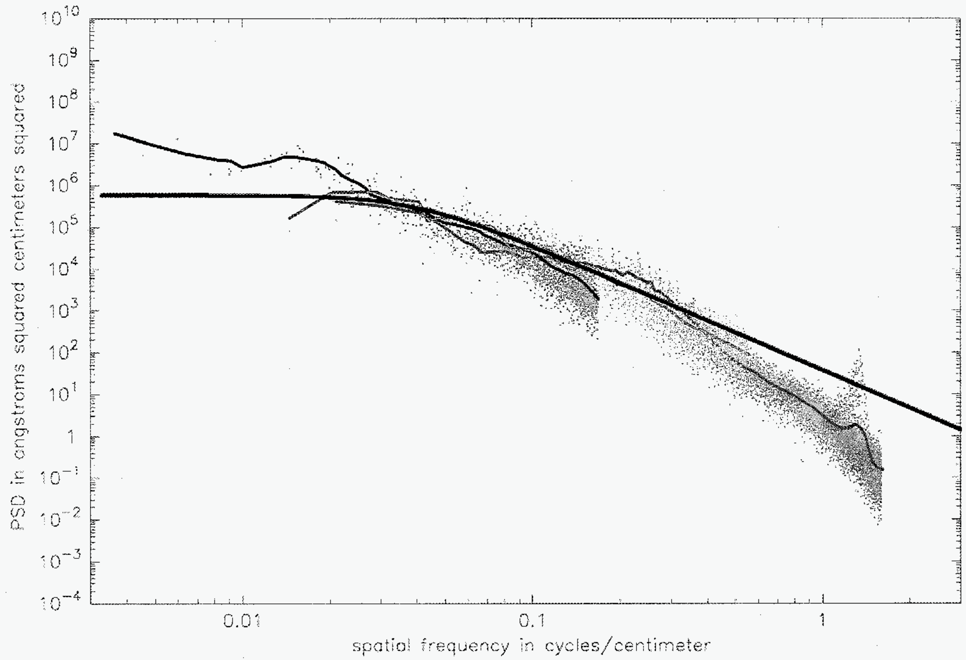


$$T(r)=\left[1-\left(\frac{2J_1(\pi r)}{\pi r}\right)^2\right]^2 \qquad T(x)=\left[1-\left(\frac{\sin(\pi x)}{\pi x}\right)^2\right]^2 \qquad T(x)=\left[\frac{2}{3}-\left(\frac{\sin(\pi x)}{\pi x}\right)^3+\frac{1}{3}\left(\frac{\sin(3\pi x)}{3\pi x}\right)\right]^2$$

Transmittance profiles for three occulting spot apodizations. From left to right: a band-limited Bessel profile, a linear sinc^2 (4th-order) profile (Kuchner and Traub 2002), and a linear 8th-order profile (Kuchner, Crepp, and Ge 2004). The linear sinc^2 and 8th-order masks have been fabricated both in HEBS glass (Canyon Materials Inc.) and as binary masks on glass at JPL's MDL.

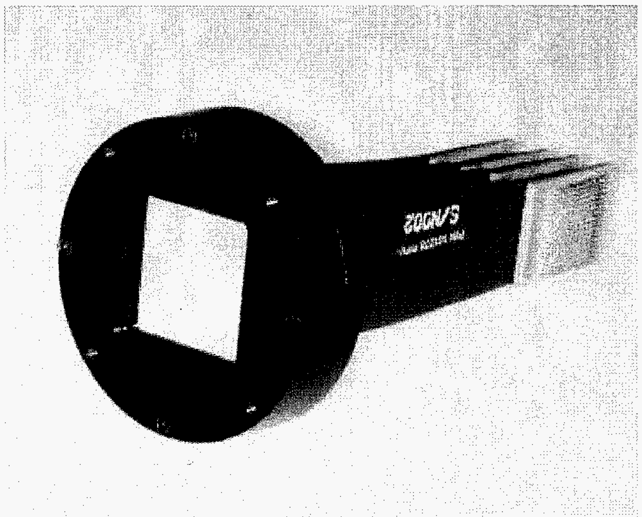
State of the Art for Large Optics



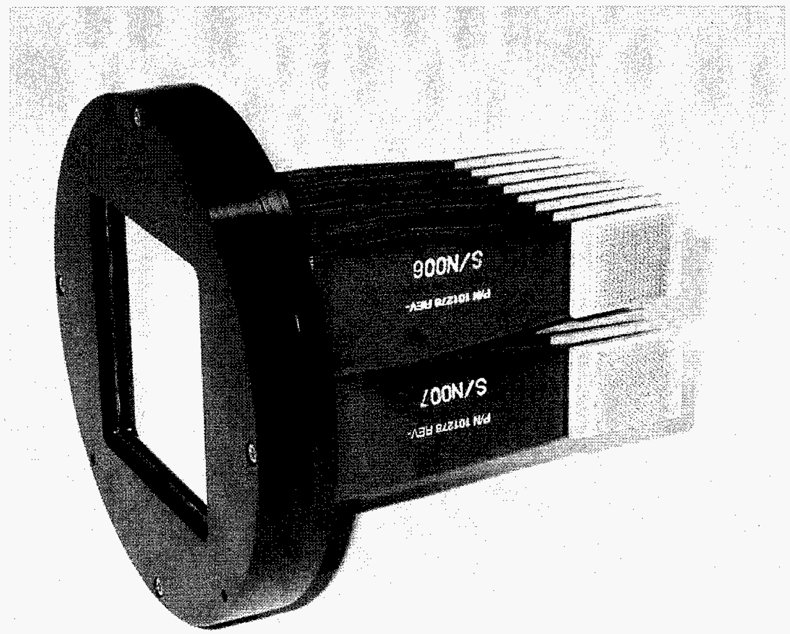


- These representative mirrors are HST (red curve), 6.5 m Magellan (blue) and a 1.5 m Kodak developmental lightweight mirror (green).
- State of the art for large mirror surface figure currently requires active correction to meet coronagraph wavefront requirements.

Eclipse optical wavefront is actively corrected

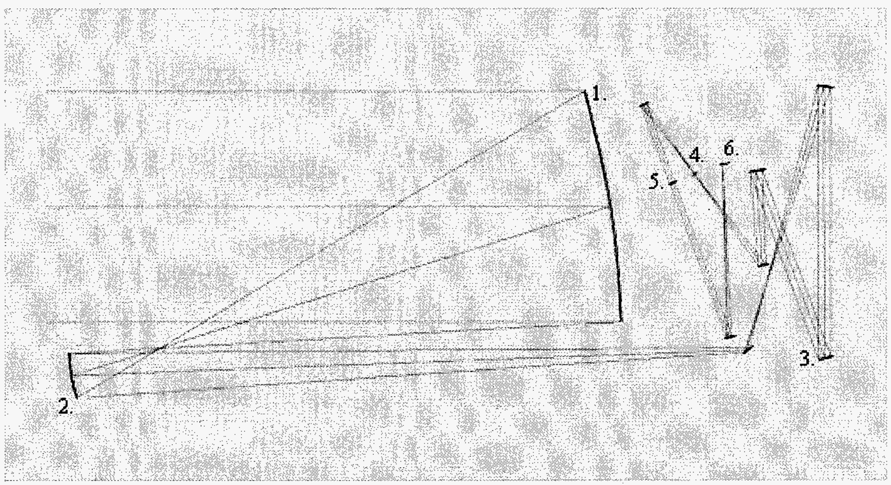


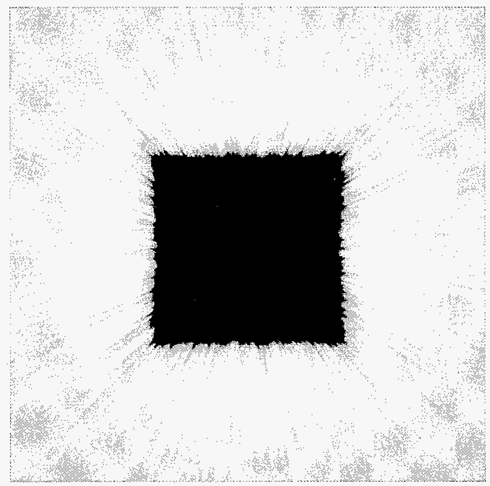
Fifth in a series of Gen2 32x32 mm DMs delivered to JPL by Xinetics. DM surface is polished to lambda/100 rms. Active figure control is better than 0.01 nm rms.



Second Gen2 64x64 mm DM delivered to JPL. Mirror is in calibration at JPL.

Eclipse design is guided by optical propagation models

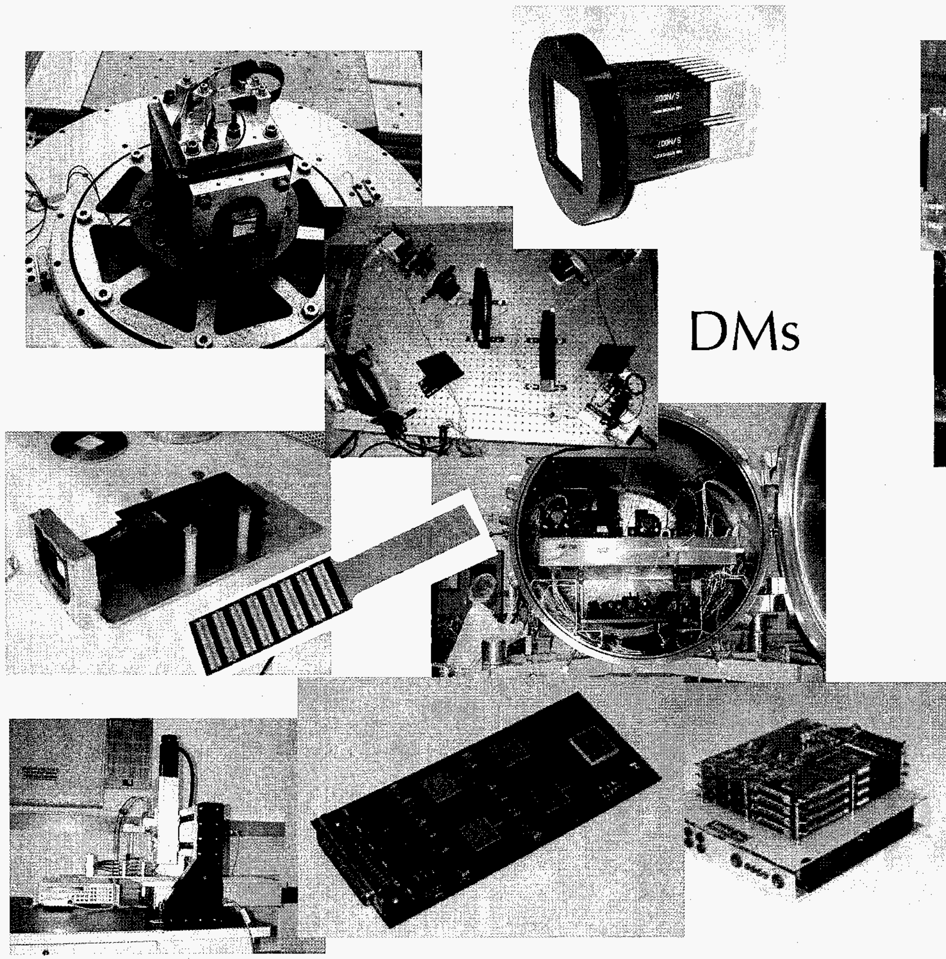




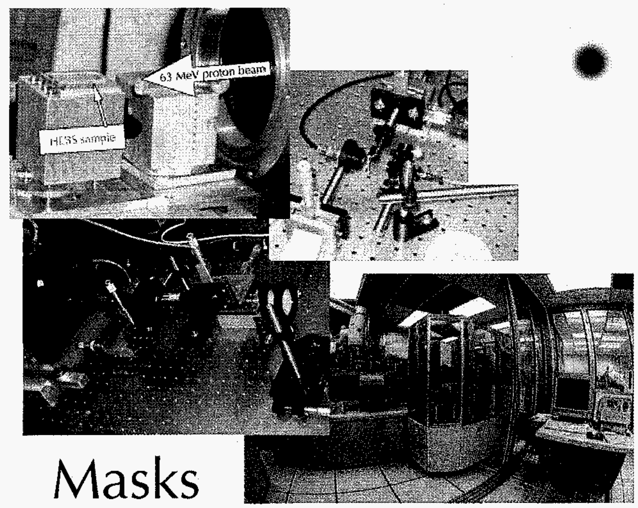
At left: The elements in the optical path of the telescope and camera are incorporated in predictive diffractive and ray-trace optical models that include representative spatial low and mid-frequency figure errors and the polarization characteristics of representative mirror coatings. DM has been adjusted to compensate for both phase errors and phase-induced amplitude errors in the wavefront, providing the deepest contrast in the lower half of the dark hole.

At right: Predicted star background (and high contrast dark hole) at the focal plane of an actively corrected coronagraphic space telescope .

Performance models are informed by laboratory characterizations

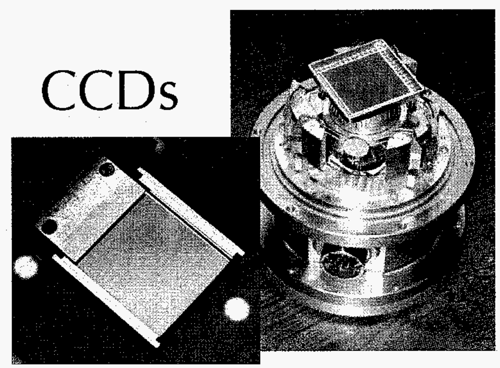


DMs



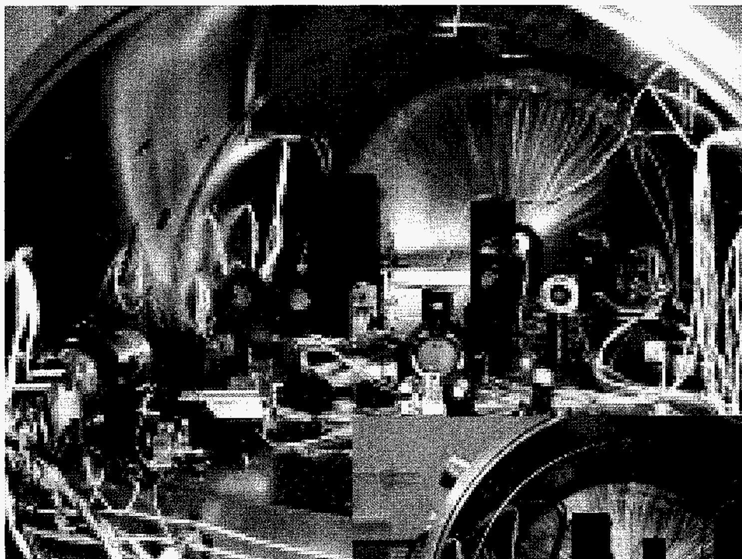
Masks

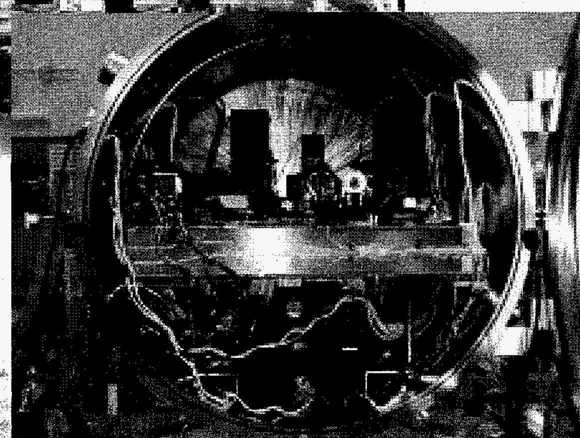
CCDs

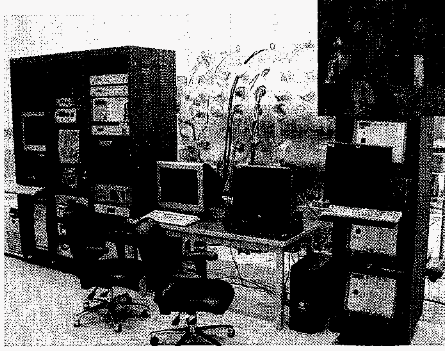


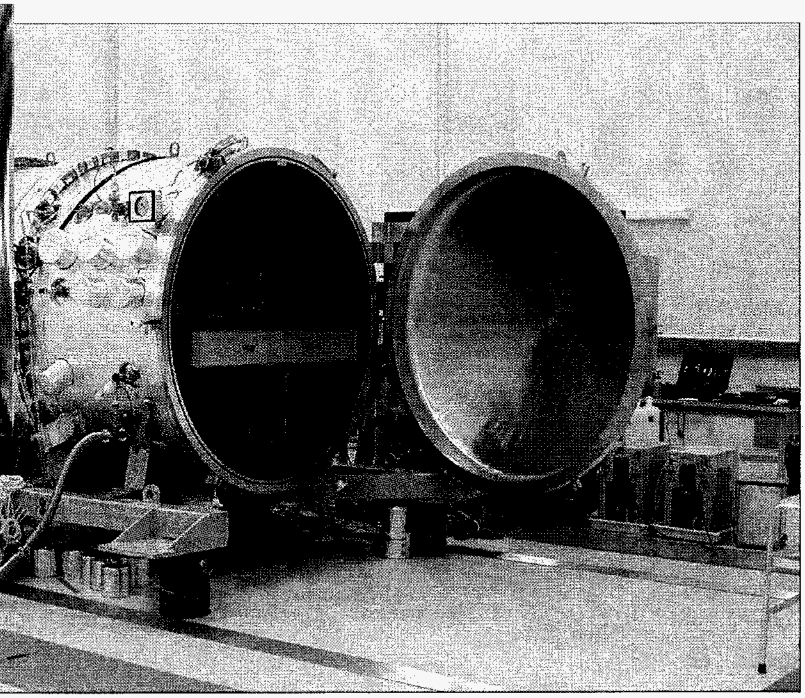
The HCIT laboratory

Optical table resides in a vibration-isolated and temperature-stabilized vacuum facility in JPL's Optical Interferometry Development Laboratory.

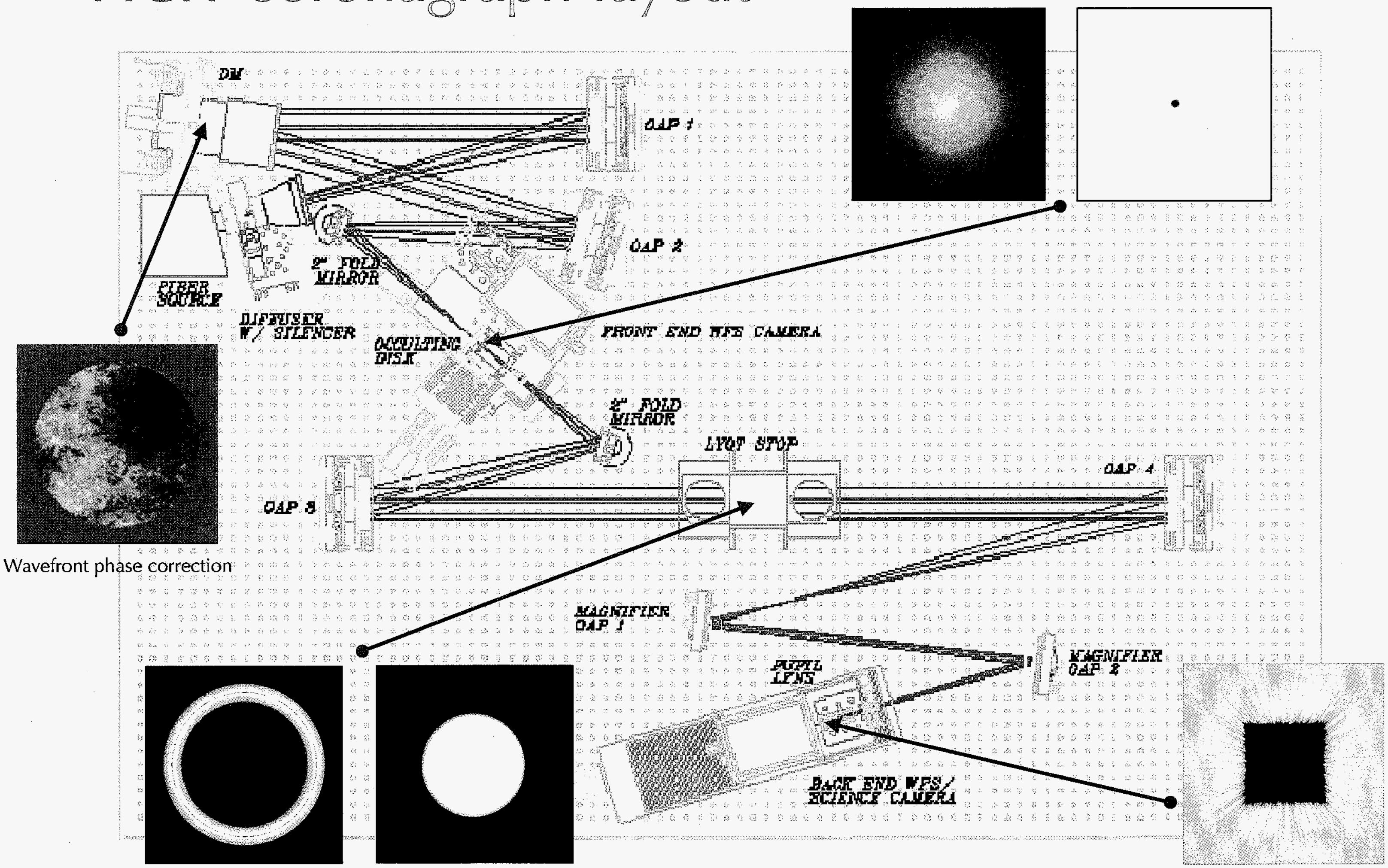








HCIT coronagraph layout



Corrected star image

Apodized occulting mask

Wavefront phase correction

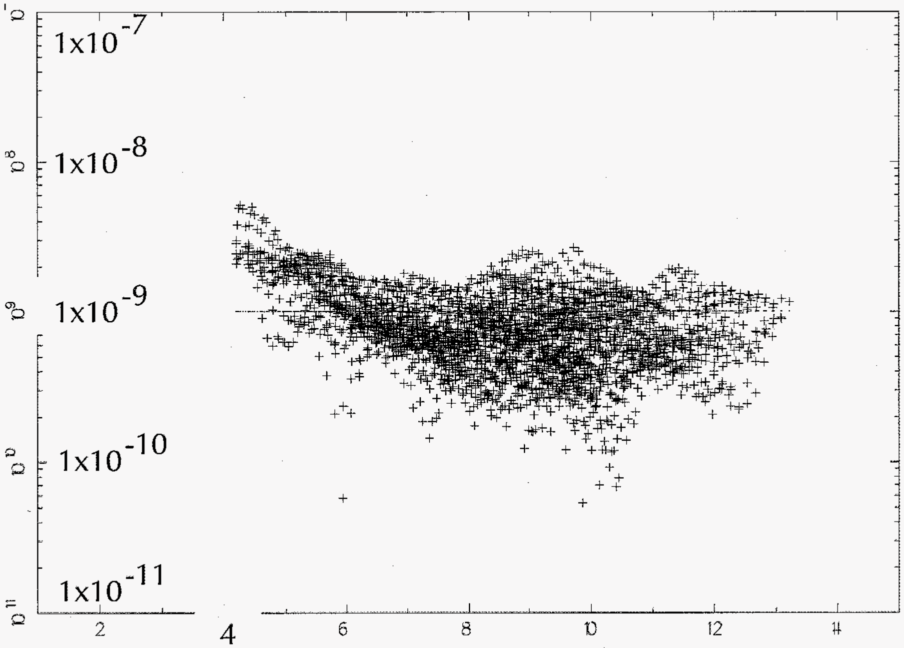
Illumination at pupil plane

Apodized lyot mask

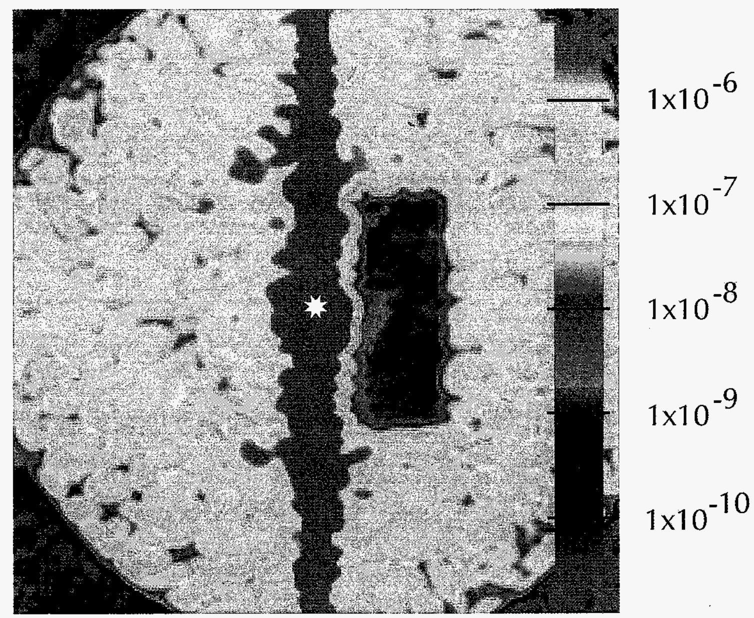
High contrast coronagraphic field

High contrast imaging in the HCIT laboratory

Coronagraph contrast within the `dark field'



Testbed contrast image

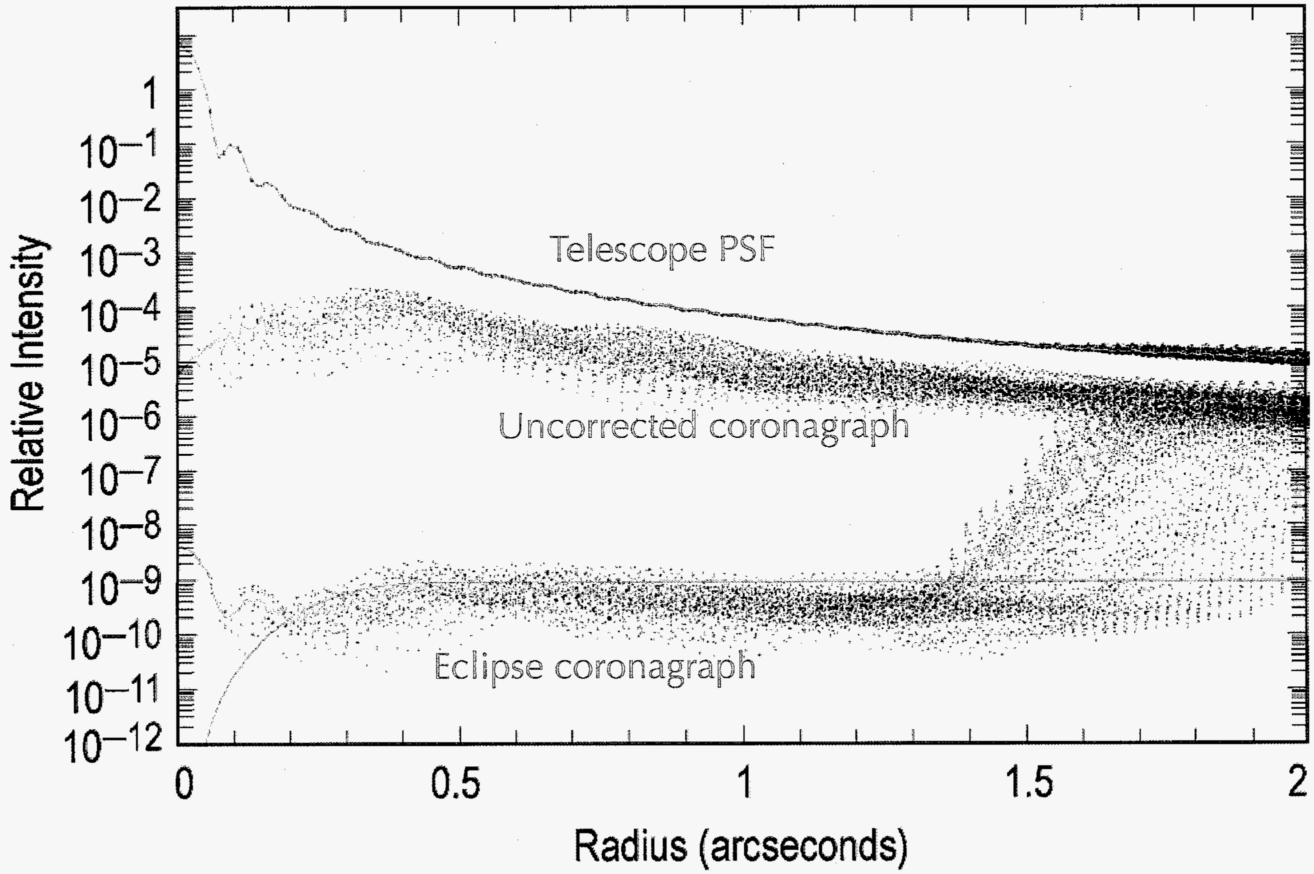


This laboratory coronagraph image was obtained with a linear occulting mask in May 2005. Inner boundary of the target box is 4 Airy radii to the right of the suppressed `star' image (star position is indicated by the star-shaped fiducial). Average intensity of background speckles in the target box is fainter than the `star' by a factor of 9×10^{-10} in 785 nm narrowband (laser) light. Contrast is stable to about 5×10^{-11} / hour with the DM actuator settings maintained open-loop at constant voltages.

End-to-end optical modeling and tolerancing

- Coronagraph modeling and optical tolerancing includes measured properties of the deformable mirror system, commercial OAP mirrors, HEBS occulting masks, and detailed TDM exploration of the state-of-the-art for a large primary mirror.
- End-to-end ray-trace analysis independently with Zemax and MACOS (Kondis / Zygo); Basinger / TPF).
- End-to-end full diffractive propagation analysis independently with SPICA and MACOS (Moody / Eclipse; Basinger / TPF).
- End-to-end polarization analysis including the detailed properties of candidate mirror coating designs (Kondis / Zygo; Pantano / ITT Kodak).
- End-to-end tolerancing of optical surface figure and alignment by combining these tools, including the conventional low-order Zernike terms plus higher order spatial mid-frequency surface figure errors.
- Optical tolerancing guides the structural and thermal designs (Hull, Kissel, Awaya, Kruid / JPL; Mehle / ATK; Egerman, Hinman / ITT Kodak).
- End-to-end system-level modeling and tolerancing are subject to laboratory validation on the HCIT.

Eclipse PSF predictions for V-band imaging



Plotted (from top to bottom respectively) are the point spread functions (PSFs) of the Eclipse 1.8 meter telescope, coronagraph, and coronagraph with active wavefront correction. Instrument contrast is 10^{-9} with an inner working angle of 0.25 arcsec for broadband (20%) visible light.

Summary

- The Eclipse concept enables a science program of direct imaging of exo-solar nearby planetary systems with emphasis on jovian-size planets and circumstellar dust/debris structures.
- Eclipse is a proposed NASA Discovery mission to perform a sensitive imaging survey of nearby planetary systems, including a survey for jovian-sized planets orbiting Sun-like stars to distances of 15 pc.
- Eclipse coronagraph and telescope architecture incorporates new technologies and new operational procedures, including:
  - Precision active wavefront (amplitude, phase, polarization) control,
  - Optimal coronagraphic apodizations,
  - Robust engineering models based on demonstrated technologies.
- The Eclipse concept development, supported by laboratory experiments, provides guidance and essential validation of the required technologies and predictive models.