National Aeronautics and Space Administration

Coronagraph Workshop 2006

Coronagraph Workshop Papers
28–29 September, 2006
Pasadena, CA

Edited by W.A. Traub

This publication was prepared by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Preface

Today's grand quest of astrophysics is to detect and characterize exoplanets. This new branch of astrophysics has stimulated a series of astonishingly clever optical solutions to the problem of observing a faint planet close to a bright star.

The first potentially viable technique for suppressing starlight, but preserving planet light, was the nulling interferometer, invented by Bracewell in 1978. This idea inspired people to think of numerous types of arrays of spacecraft that could collect and phase-shift light in order to null out the star efficiently. These designs culminated in the Terrestrial Planet Finder Interferometer (Beichman et al., 1999) in the US, and the Darwin project (Fridlund, 2000) in Europe. For several years it was widely believed that this general architecture, with multiple spacecraft, was the only practical way to suppress starlight sufficiently to see a companion planet. Although these are still exciting and viable designs, we now have several alternatives, as we will explore in this volume.

The idea of using a telescope incorporating a blocking disc (to suppress the light of a bright source but still be able to see faint structures nearby) was invented by Bernard Lyot in 1933 to observe the solar corona. Since that time all descendents of Lyot's telescope have been called coronagraphs, whether the blocker is external or internal or accomplished virtually by means of a pi phase shift. Lyot's design worked well enough for the sun and corona, where the angular separation (~0.5 degree) was relatively large and the contrast ($\sim 10^{-6}$) relatively modest, but today's needs are greater.

Exoplanet observations will demand much more of a coronagraph. For an Earth-Sun twin at 10 pc, for example, the separation is smaller (~0.1 arcsec) and the contrast more extreme ($\sim 10^{-10}$), both by factors of tens of thousands.

The main technical issues of an exoplanet coronagraph are: (1) the Airy diffraction rings must be suppressed; (2) the scattered light speckles must be suppressed; (3) the design must be able to tolerate a finite-sized star and pointing error; (4) the design must work with a finite wavelength band; (5) the design must be able to tolerate realistic background zodiacal light levels; (6) the design must support spectroscopy; (7) the design will preferably allow general astrophysical observations in addition to exoplanets.

Further practical issues include fabrication, testing, validation, risk, cost, flight operations, observing efficiency, and scientific yield.

To meet these challenges, roughly a score of new optical designs for coronagraphs have been proposed, none of which yet appear in any textbooks, but most of which are discussed in this volume.

By summer of 2006 it was clear that many exoplanets had been discovered, and that it was likely (but not yet proven) that there were many terrestrial planets waiting to be discovered in the habitable zones around nearby stars. It was also clear that there were many new coronagraph designs that could potentially detect and characterize these terrestrial planets. What was lacking, however, was an evaluation of how these designs measured up to the 7 criteria listed above.

To begin to answer these questions, many of the world's leading coronagraph experts gathered in Pasadena in the fall of 2006 to explain, compare, and evaluate these designs. Soon after the workshop these experts also provided written versions of their presentations, which are collected here.

The good news from this workshop is that there are several types of coronagraph that are theoretically attractive, and that there is at least one laboratory result showing that the direct imaging of Earth-like exoplanets is nearly within reach.

The current volume is a fall-2006 snapshot of the state of coronagraphic art. We open with a group photo of participants, with a list of names and email addresses, to facilitate community connections. The papers then follow in three major sections.

The first section contains four overview papers: a theoretical analysis of coronagraph types; the optical requirements of coronagraphs; a review of current laboratory testbeds (adapted by invitation from a paper delivered at the TPF-Darwin meeting in November 2006); and an invited commentary on the state-of-the-art of coronagraphy.

The second section contains 21 papers on lessons learned with coronagraphs in the lab, at ground-based telescopes, and expected in space.

The third section contains 6 papers that focus on the theoretically best types of coronagraphs: the shaped pupil design, the nulling coronagraph, band-limited mask coronagraphs, the optical vortex coronagraph, the phase-induced amplitude apodization (or pupil mapping) coronagraph, and the external occulter coronagraph.

This volume is JPL Publication 07-02, available by request from the editor. An on-line version of this volume, as well as the presentation charts from which the written papers were derived, are available at http://planetquest.jpl.nasa.gov/TPF/tpf-c_workshopDocs.cfm.

Wesley A. Traub, editor
15 June 2007

REFERENCES

Beichman, C.A., N.J. Woolf, and C.A. Lindensmith, eds., 1999, Terrestrial Planet Finder, JPL Publication 99-3, http://planetquest.jpl.nasa.gov/TPF/tpf_book/index.cfm.

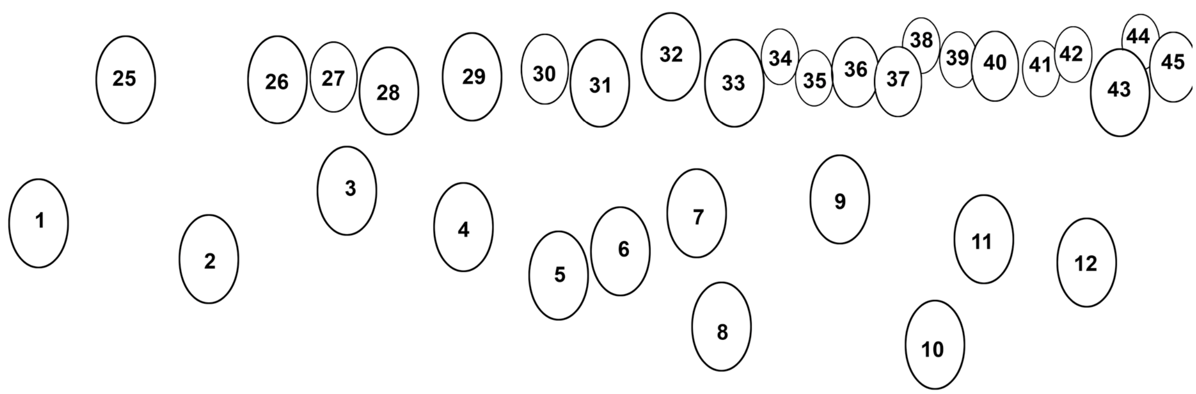
Bracewell, R., 1978, Detecting nonsolar planets by spinning infrared interferometer, Nature **274**, pp.780–781.

Fridlund, M., 2000, in DARWIN: The Infrared Space Interferometer, ESA SCI-12, Noordwijk, ESA, 47.

Lyot, B., 1933, The study of the solar corona without an eclipse, J. Royal Astronomical Society of Canada, **27**, pp. 265–280.

Today 2½ years after the Coronagraph Workshop met, the papers in this volume are still highly relevant. This edition includes important corrections to the author lists of two papers, plus a handful of fixed typos. WAT, 18 June 2009

Coronograph Workshop Attendees Photo

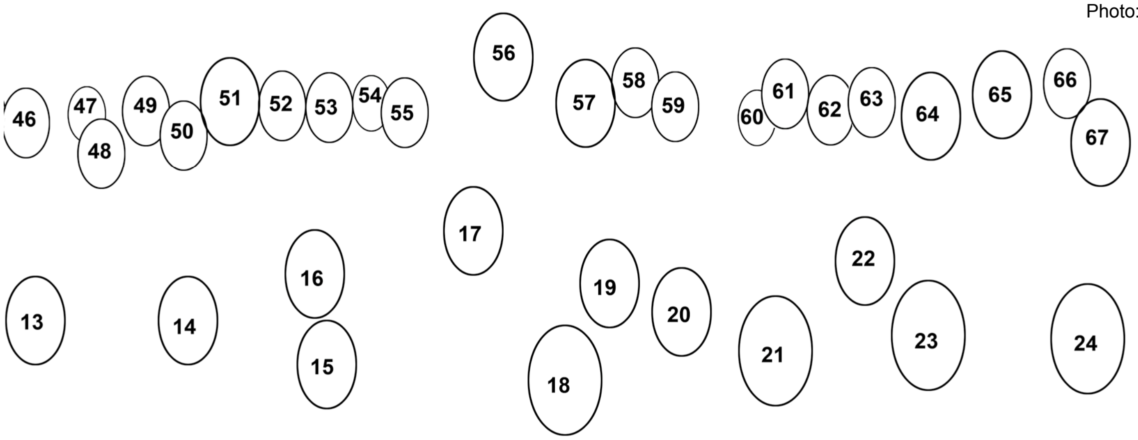


Attendees at the Exoplanet Detection with Coronagraphs 2006 Workshop. See the following list of attendees for the key to names (photo).

First Name	Last Name	Photo #
Egemen	Kolemen	1
Lyu	Abe	2
Jason	Kay	3
Sarah	Hunyadi	4
Robert	Egerman	5
Jun	Nishikawa	6
Eric	Cady	7
Olivier	Guyon	8
Wesley	Traub	9
Joseph	Carson	10
Mark	Swain	11
Gary	Matthews	12
Jon	Arenberg	13
Stuart	Shaklan	14
Jian	Ge	15
Motohide	Tamura	16

First Name	Last Name	Photo #
Ian	Crossfield	17
Justin	Crepp	18
Ruslan	Belikov	20
Richard	Lyon	21
Dwight	Moody	22
Grover	Swartzlander	23
David	Palacios	24
Robert	Vanderbei	25
Pascal	Borde	26
Shinichiro	Tanaka	27
Pierre	Baudoz	28
Bala	Balasubramanian	29
Remi	Soummer	30
Dominick	Tenerelli	31
Robert	Brown	32
Marie	Levine	33

Photo: G. Swartzlander



First Name	Last Name	Photo #
Tom	Roellig	34
Rocco	Samuele	35
Kent	Wallace	36
Michael	Shao	37
Michael	Devirian	38
Jean	Schneider	39
Brian	Kern	40
Marty	Levine	41
John	Trauger	42
Marc	Kuchner	43
Karl	Stapelfeldt	45
Roger	Angel	46
John	Krist	47
Beth	Biller	48
Zlatan	Tsvetanov	49
Allan	Eisenman	50
Steven	Beckwith	51

First Name	Last Name	Photo #
Joe	Pitman	52
Laurent	Pueyo	53
Chuck	Bowers	54
Amir	Give'on	55
Frantz	Martinache	56
Dimitri	Mawet	57
Charley	Noecker	58
Anthony	Boccaletti	59
Eugene	Pluzhnik	60
Jeremy	Kasdin	61
Gene	Serabyn	62
Bob	Woodruff	63
Martin	Lo	64
Chuck	Lillie	65
Steven	Ridgway	66
Peggy	Park	67

Last Name	First Name	Organization	E-mail
Abe	Lyu	NAOJ	abe@optik.mtk.nao.ac.jp
Angel	Roger	Univ of Arizona	rangel@as.arizona.edu
Arenberg	Jon	NGST	jon.arenberg@ngc.com
Balasubramanian	Bala	JPL	kbala@jpl.nasa.gov
Baudoz	Pierre	Observatoire de Meudon	baudoz@mesiog.obspm.fr
Beckwith	Steven	STSci	svwb@stsci.edu
Beichman	Chas	JPL / MSC / Caltech	chas@mail.jpl.nasa.gov
Belikov	Ruslan	Princeton	rbelikov@Princeton.EDU
Biller	Beth	Univ of Arizona	bbiller@coatlicue.as.arizona.edu
Boccaletti	Anthony	Observatoire de Meudon	anthony.boccaletti@obspm.fr
Borde	Pascal	Harvard CFA	pborde@cfa.harvard.edu
Bowers	Chuck	GSFC	Charles.W.Bowers@nasa.gov
Breckinridge	James	JPL	jbreckin@mail.jpl.nasa.gov
Brown	Robert	STSci	rbrown@stsci.edu
Cady	Eric	Princeton	ecady@princeton.edu
Carson	Joseph	JPL	Joseph.C.Carson@jpl.nasa.gov
Cash	Webster	Univ of Colorado	cash@origins.colorado.edu
Clampin	Mark	GSFC	mark.clampin@nasa.gov
Codona	John	Univ of Arizona	jcodona@as.arizona.edu
Cohen	Eri	JPL	Eri.J.Cohen@jpl.nasa.gov
Coulter	Dan	JPL	Daniel.R.Coulter@jpl.nasa.gov
Crepp	Justin	Univ of Florida	jcrepp@astro.ufl.edu
Crossfield	Ian	JPL	Ian.J.Crossfield@jpl.nasa.gov
Dekany	Richard	Caltech	rgd@astro.caltech.edu
Devirian	Michael	JPL	devirian@jpl.nasa.gov
Egerman	Robert	ITT	Robert.Egerman@itt.com
Eisenman	Allan	JPL	Allan.R.Eisenman@jpl.nasa.gov
Enya	Keigo	JAXA	enya@ir.isas.jaxa.jp
Ftaclas	Christ	Univ of Hawaii	ftaclas@ifa.hawaii.edu
Ge	Jian	Univ of Florida	jge@astro.ufl.edu
Give'on	Amir	Caltech	agiveon@caltech.edu
Green	Joe	JPL	Joseph.J.Green@jpl.nasa.gov
Guyon	Olivier	Subaru Telescope, NOAJ	guyon@subaru.naoj.org
Hong	John	JPL	John.H.Hong@jpl.nasa.gov
Hoppe	Dan	JPL	Daniel.J.Hoppe@jpl.nasa.gov
Hunyadi	Sarah	JPL	Sarah.Hunyadi@jpl.nasa.gov
Johnson	Bill	JPL	william.r.johnson@jpl.nasa.gov
Kasdin	Jeremy	Princeton	jkasdin@Princeton.EDU
Kay	Jason	Princeton	jkay@princeton.edu
Kern	Brian	JPL	Brian.D.Kern@jpl.nasa.gov
Kolemen	Egemen	Princeton	ekolemen@princeton.edu
Krist	John	JPL	krist@jpl.nasa.gov
Kuchner	Marc	GSFC	mkuchner@milkyway.gsfc.nasa.gov
Kuhnert	Andy	JPL	Andreas.C.Kuhnert@jpl.nasa.gov
Labeyrie	Antoine	OHP	labeyrie@obs-hp.fr
Lawson	Peter	JPL	Peter.R.Lawson@jpl.nasa.gov
Levine	Marie	JPL	marie.levine@jpl.nasa.gov
Levine	Marty	JPL	bmlevine@s383.jpl.nasa.gov
Lillie	Chuck	NGST	chuck.lillie@ngc.com

Last Name	First Name	Organization	E-mail
Lo	Martin	JPL	martin.lo@jpl.nasa.gov
Lyon	Richard	GSFC	Richard.G.Lyon@nasa.gov
Macintosh	Bruce	LLNL	bmac@igpp.ucllnl.org
Martinache	Frantz	Cornell	frantz@astro.cornell.edu
Matthews	Gary	ITT	Gary.Matthews@itt.com
Mawet	Dimitri	Liege	mawet@astro.ulg.ac.be
Milman	Mark	JPL	mark.milman@jpl.nasa.gov
Moody	Dwight	JPL	dwight.moody@jpl.nasa.gov
Nielsen	Eric	Steward Observatory, Univ of Arizona	enielsen@omoikane.as.arizona.edu
Nishikawa	Jun	NAOJ	jun.nishikawa@nao.ac.jp
Noecker	Charley	Ball Aerospace	mcnoecke@ball.com
Palacios	David	JPL	david.palacios@jpl.nasa.gov
Park	Peggy	JPL	Peggy.H.Park@jpl.nasa.gov
Pitman	Joe	Lockheed Martin	joe.pitman@lmco.com
Pluzhnik	Eugene	NAOJ	epluzhnyk@keck.hawaii.edu
Pueyo	Laurent	Princeton	lpueyo@princeton.edu
Ridgway	Steven	NOAO	ridgway@noao.edu
Roellig	Tom	NASA Ames	troellig@mail.arc.nasa.gov
Samuele	Rocco	NGST	rsamuele@huey.jpl.nasa.gov
Schneider	Jean	Observatoire de Meudon	Jean.Schneider@obspm.fr
Serabyn	Gene	JPL	gene.serabyn@jpl.nasa.gov
Shaklan	Stuart	JPL	shaklan@s383.jpl.nasa.gov
Shao	Michael	JPL	mshao@s383.jpl.nasa.gov
Sidick	Erkin	JPL	Erkin.Sidick@jpl.nasa.gov
Soummer	Remi	American Museum of Natural History	rsoummer@amnh.org
Stapelfeldt	Karl	JPL	krs@exoplanet.jpl.nasa.gov
Swain	Mark	JPL	swain@mpia-hd.mpg.de
Swartzlander	Grover	Univ of Arizona	grovers@optics.arizona.edu
Tamura	Motohide	NOAJ	hide@optik.mtk.nao.ac.jp
Tanaka	Shinichiro	JAXA	stanaka@ir.isas.jaxa.jp
Tenerelli	Dominick	Lockheed Martin	dominick.tenerelli@lmco.com
Traub	Wesley	JPL	Wesley.A.Traub@jpl.nasa.gov
Trauger	John	JPL	John.T.Trauger@jpl.nasa.gov
Tsvetanov	Zlatan	NASA Headquarters	zlatan.tsvetanov@nasa.gov
Unwin	Steven	JPL	Stephen.C.Unwin@jpl.nasa.gov
van Zyl	Jakob	JPL	Jakob.J.vanZyl@jpl.nasa.gov
Vanderbei	Robert	Princeton	rvdb@Princeton.EDU
Wallace	Kent	JPL	James.K.Wallace@jpl.nasa.gov
Werner	Michael	JPL	mwerner@sirtfweb.jpl.nasa.gov
Wilson	Daniel	JPL	daniel.w.wilson@jpl.nasa.gov
Woodruff	Bob	Lockheed Martin	robert.a.woodruff@lmco.com

Table of Contents

1. Overview Papers

2. Lessons Learned with Coronagraphs

3. Reviews of Leading Coronagraph Types

"Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets"

… from the NASA Science Plan for 2007, Astrophysics Sub-goal

For more information on NASA's Navigator Program, visit:

http://planetquest.jpl.nasa.gov

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

JPL Publication 07-02 7/07