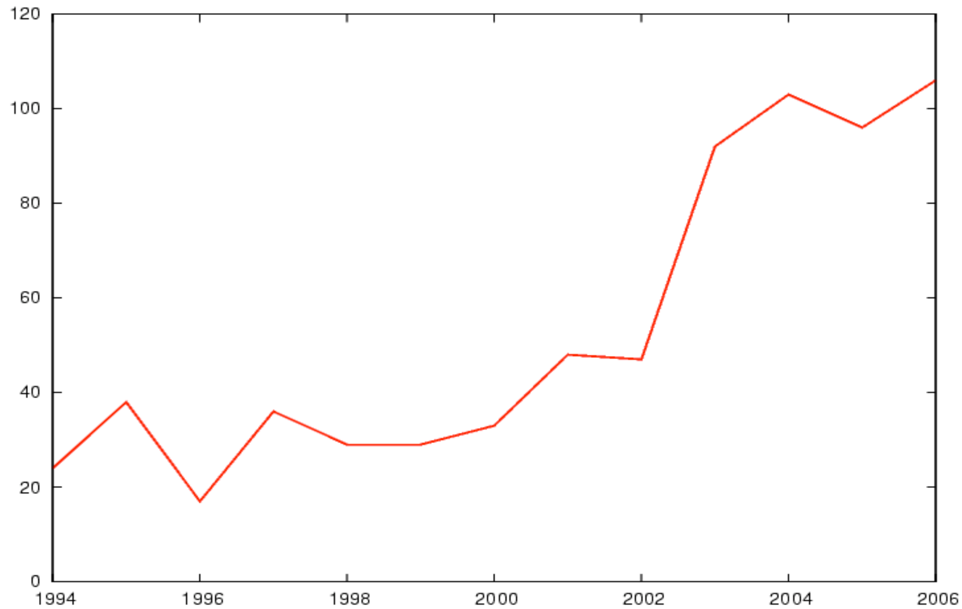
The Coronagraph Tree of Life
(non-solar coronagraphs)

Olivier Guyon (Subaru Telescope)
guyon@naoj.org

Quick overview of coronagraph designs
attempt to group coronagraphs in broad families

Where is the performance limit ? What sets this limit ?
Source characteristics, wavefront quality ...

ADS hits with “coronagraph/coronagraphy” in title



Exoplanets

How many planets around other stars ?
How do they form, evolved ?
Mass, size, composition ?
Rocky planets with atmospheres ?

Could have life evolved on other planets ?
Intelligent life somewhere else ?

Direct imaging of planets similar to the ones in our solar system is very difficult

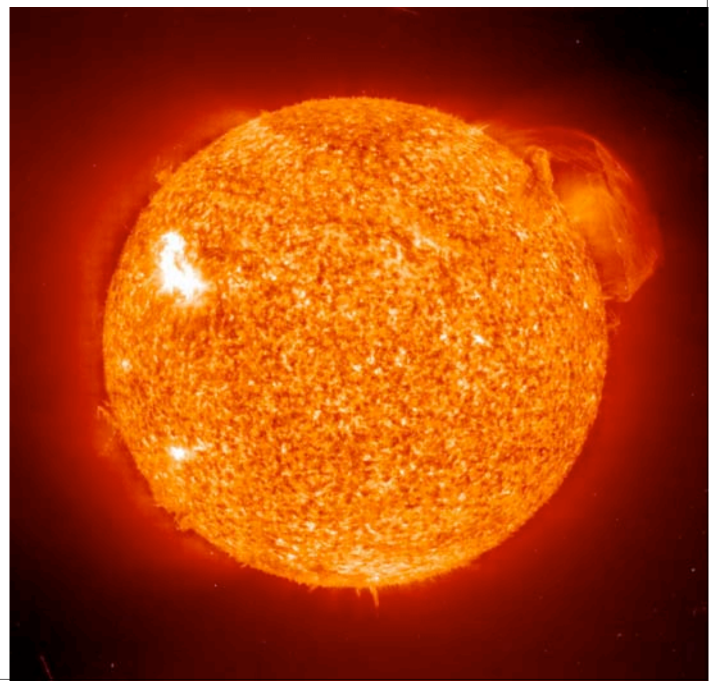
A planet is faint (compared to its star) and very close to its star.

In visible:

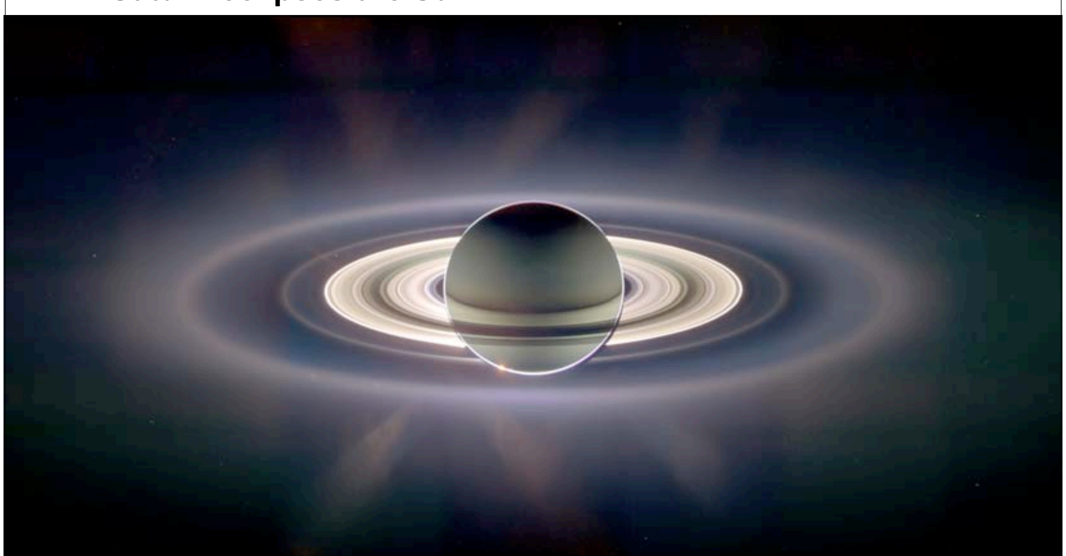
Earth is 1e10 times fainter than Sun
Jupiter is 1e9 times fainter than Sun

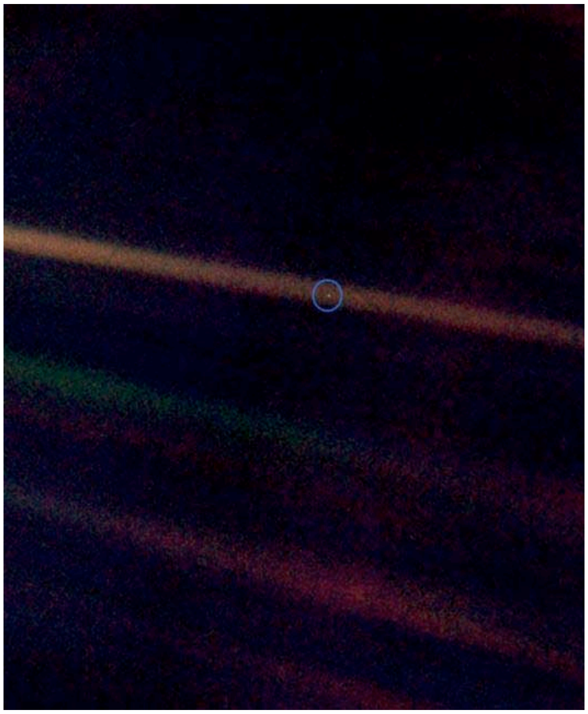
In IR (10 um):

Sun/Earth = 1e6



Saturn eclipses the Sun





Earth as seen
by Voyager 1

Many Coronagraph Choices...

CORONAGRAPHS ABLE TO ACHIEVE 10^{10} PSF CONTRAST WITHIN 5 λ/d

Coronagraph	abrev.	reference	Design(s) adopted
"Interferometric" Coronagraphs			
Achromatic Interferometric Coronagraph	AIC	Baudoz et al. (2000)	
Common-Path Achromatic Interferometer-Coronagraph	CPAIC	Tavrov et al. (2005)	(=AIC)
Visible Nulling Coronagraph, X-Y shear (4^{th} order null)[a]	VNC	Mennesson et al. (2003)	Shear distance = ±0.3 pupil radius
Pupil Swapping Coronagraph	PSC	Guyon & Shao (2006)	Shear distance = 0.4 pupil diameter
Pupil apodization			
Conventional Pupil Apodization and Shaped-Pupil[b]	CPA	Kasdin et al. (2003)	Prolate[c]($r = 4.2\lambda/d$, 8% throughput)
Achromatic Pupil Phase Apodization	PPA	Yang & Kostinski (2004)	$\phi = \phi_2(x) + \phi_2(y)$; $a = 2$; $\epsilon = 0.01$
Phase Induced Amplitude Apodization Coronagraph	PIAAC	Guyon (2003)	Prolate apodization
Phase Induced Zonal Zernike Apodization	PIZZA	Martinache (2004)	Not simulated
Improvement on the Lyot concept with amplitude masks			
Apodized Pupil Lyot Coronagraph	APLC	Soummer et al. (2003)	$r = 1.8\lambda/d$
Apodized Pupil Lyot Coronagraph, N steps	$APLC_N$	Aime & Soummer (2004)	$(N, r) = (2, 1.4); (3, 1.2); (4, 1.0)$
Band limited, 4^{th} order[a]	BL4	Kuchner & Traub (2002)	$\sin^4$ intensity mask, $\epsilon = 0.21$
Band limited, 8^{th} order	BL8	Kuchner et al. (2005)	$m = 1, l = 3, \epsilon = 0.6$
Improvement on the Lyot concept with phase masks			
Phase Mask	PM	Roddier & Roddier (1997)	with mild prolate pupil apod.
4 quadrant	4QPM	Rouan et al. (2000)	
Achromatic Phase Knife Coronagraph	APKC	Abe et al. (2001)	(=4QPM)
Optical Vortex Coronagraph, topological charge m	OVC_m	Palacios (2005)	$m = 2, 4, 6, 8$
Angular Groove Phase Mask Coronagraph	AGPMC	Mawet et al. (2005)	(=OVC)
Optical Differentiation	ODC	Oti et al. (2005)	mask: $x \times \exp^{-(x/10)^2}$[d]

[a]The Visible Nulling Coronagraph (VNC) and Band limited 4^{th} order (BL4) coronagraphs belong to the same class of pupil-shearing 4^{th} order coronagraphs, and are simply 2 ways of achieving the same result. They can be designed to have exactly the same performance. In this Table, the VNC is chosen with a small IWA and 2 orthogonal shear directions, while the BL4 is designed with a larger IWA and 2 shears in the same direction. To reflect this similarity, they are referred to as VNC/BL4(1) for the small IWA option (listed as VNC in this Table) and VNC/BL4(2) for the large IWA option (listed as BL4 in this Table).

[b]The CPA design adopted here is a continuous apodization (rather than binary apodization/shaped pupil) which maximizes the radially averaged performance at $\approx 4\lambda/d$. More optimal designs exist in other conditions: CPA with high contrast at specific position angles for observations at $\approx 3\lambda/d$ or high throughput CPA for observations at $> 4\lambda/d$.

[c]CPA, APLC, $APLC_N$: r is the radius, in λ/d, of the mask within which the circular prolate function is invariant to a Hankel transform. This parameter is half of the mask diameter a defined in Soummer et al. (2003).

[d]ODC: x is in λ/d. Maximum mask transmission at $7\lambda/d$. Lyot pupil mask radius = 0.85 times pupil radius.

4 main branches, 4 different approaches

"Interferometric" coronagraphs

Achromatic Interferometric Coronagraph	AIC
Common Path AIC	CPAIC
Visible Nulling Coronagraph, X & Y shear, 4th order	VNC
Pupil Swapping Coronagraph	PSC

Pupil Apodization

Conventional Pupil Apodization/ Shaped pupil	CPA
Achromatic Pupil Phase Apodization	PPA
Phase Induced Amplitude Apodization Coronagraph	PIAA
Phase Induced Zonal Zernike Apodization	PIZZA

Lyot coronagraph & Improvements on the Lyot concept

	Lyot Coronagraph	LC
amplitude	Apodized Pupil Lyot Coronagraph	APLC
amplitude	Multistep APLC	APLCn
amplitude	Band Limited, 4th order	BL4
amplitude	Band Limited, 8th order	BL8
Phase	Phase mask	PM
Phase	4 quadrant	4QPM
Phase	Achromatic Phase Knife Coronagraph	APKC
Phase	Optical Vortex Coronagraph, topological charge m	OVCm
Phase	Angular Groove Phase Mask Coronagraph	AGPMC
Phase	Optical Differenciation Coronagraph	ODC

External Occulter

"Interferometric" coronagraphs

= Nulling interferometer on a single pupil telescope

- Creates multiple (at least 2) beams from a single telescope beam
- Combines them to produce a destructive interference on-axis and constructive interference off-axis

Achromatic Interferometric Coronagraph **AIC**
Common Path AIC **CPAIC**

Baudoz et al. 2000, Tavrov et al. 2005

Destructive interference between pupil and flipped copy of the pupil
Achromatic PI phase shift and geometrical flip performed by going through focus

Visible Nulling Coronagraph, X & Y shear, 4th order **VNC**

Shao et al., Menesson et al. 2003

Destructive interference between 2 copies of the pupil, sheared by some distance.
4th order null obtained by cascading 2 shear/null

Pupil Swapping Coronagraph **PSC**

Guyon & Shao, 2006

Destructive interference between pupil and a copy of the pupil where 4 quadrants have been swapped ic interfero coronagraphy. I.

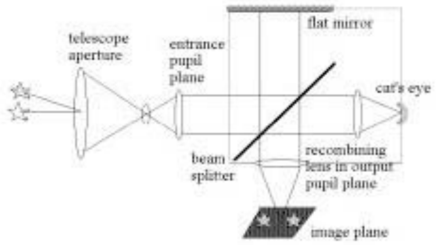


Fig. 1. Schematic of the Generic Set-up of our coronagraph

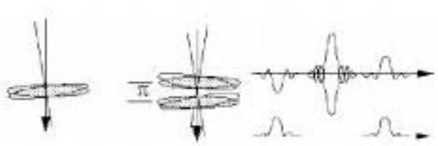


Fig. 2. Left: collected wavefronts, one from the central source the other (tilted) from a companion. Center: wavefronts on the recombiner lens. Right: amplitudes and resulting intensity in image plane

hromatic Interferometric ronagraph (AIC)

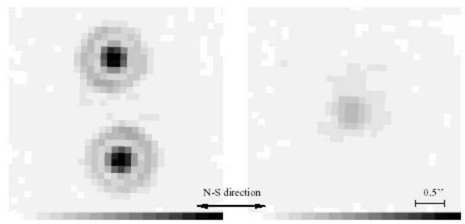
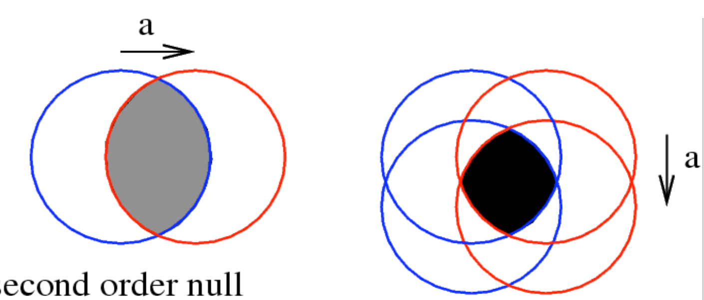


Fig. 3. Image of a star off-axis and on-axis. The scale is linear and is the same for the 2 images

Used on sky (CFHT)

Gay & Rabbia 1996, C.R. Acad. Sci. Paris 322, 265
Baudoz et al. 2000, A&AS, 141, 319
Baudoz et al. 2005, PASP, 117, 1004 (Hybrid AIC, no 180 deg ambiguity)
Tavrov et al. 2005, Opt. Letters, 30, 2224 (Common path AIC)

Visible Nuller Coron. (VNC)



second order null
phase offset prop. to
pupil shear x source offset

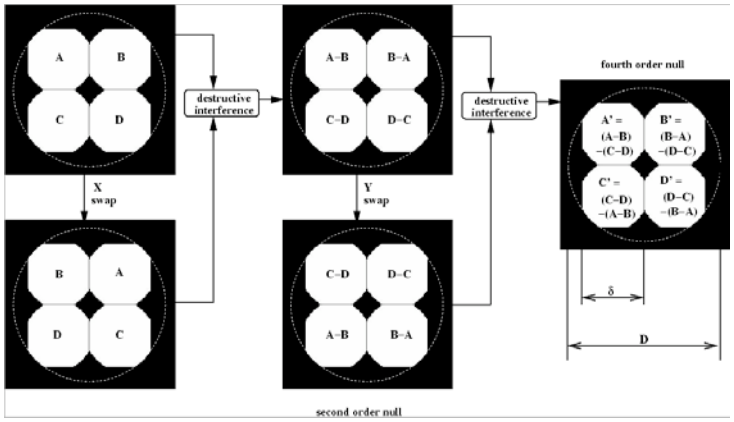
4th order null

Small shear : high throughput, low IWA
Large shear : low throughput, small IWA
The 2 shears can also be colinear

Will fly soon
on sounding rocket
(PICTURE)

Mennesson, Shao ... 2003, SPIE 4860, 32

Pupil Swapping Coronagraph (PSC)



Same basic principle as VNC, higher throughput

Guyon & Shao, 2006, PASP

Pupil Apodization

Since Airy rings originate from sharp edges of the pupil, why not change the pupil ?

Conventional Pupil Apodization/ Shaped pupil CPA

Kasdin et al. 2003

Make the pupil edges fainter by absorbing light, either with a continuous or "binary" (shaped pupil) mask

Achromatic Pupil Phase Apodization PPA

Yang & Kostinski, 2004

Same as CPA, but achieved by a phase apodization rather than amplitude

Phase Induced Amplitude Apodization Coronagraph PIAAC

Guyon, 2003

Perform amplitude apodization by remapping of the pupil with aspheric optics

Phase Induced Zonal Zernike Apodization PIZZA

Martinache, 2003

Transform a pupil phase offset into an amplitude apodization thanks to a focal plane Zernike mask

Conventional Pupil Apodization (CPA)

Many pupil apodizations have been proposed.

Apodization can be continuous or binary.

+ Simple, robust, achromatic
- low efficiency for high contrast

Jacquinot & Roisin-Dossier 1964
Kasdin et al. 2003, ApJ, 582, 1147
Vanderbei et al. 2003, ApJ, 590, 593
Vanderbei et al. 2003, ApJ, 599, 686
Vanderbei et al. 2004, ApJ, 615, 555

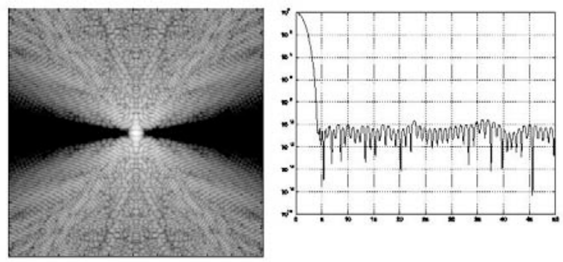


FIG. 9.—*Top*: Asymmetric multiopening mask designed to provide high contrast, 10^{-10}, from $\lambda/D = 4$ to $\lambda/D = 100$ in two angular sectors centered on the *x*-axis. Ten integrations are required to cover all angles. Total throughput and pseudoarea are 24.4%. Airy throughput is 11.85%. *Bottom*: Associated PSF. (Note that this mask was originally designed for an elliptical mirror. It has been rescaled to fit a circular aperture.)

Pupil Phase Apodization (PPA)

Achromatic solutions exist.

Yang & Kostinski 2004, ApJ, 605, 892
Codona & Angel 2004, ApJ, 604, L117

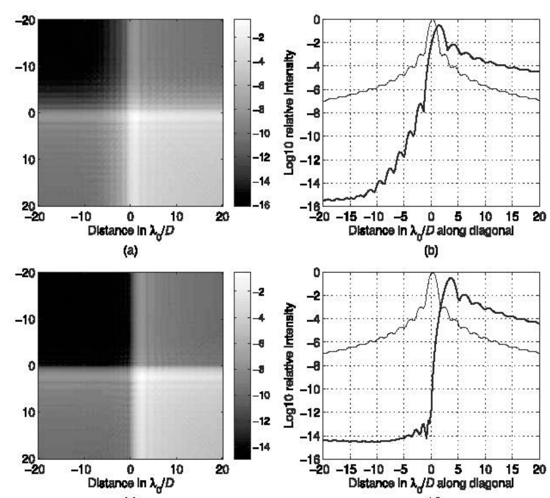
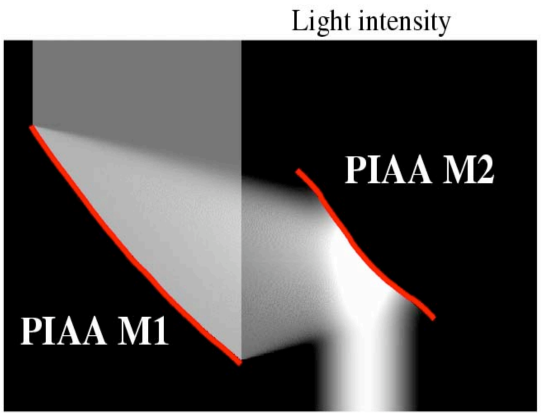
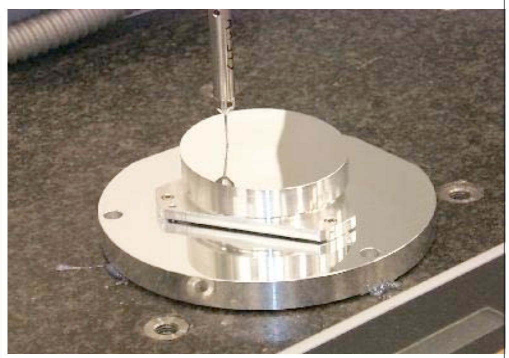


FIG. 9.—Broad-bandwidth light reduction effect on one quadrant of focal plane. The simulation is based on a rectangular spectrum distribution with total bandwidth of $0.6\lambda_0$. (*a*) $\log_{10}$ relative intensity image when phase $\phi(x, y) = a\tan[(0.5 - \epsilon)2\pi x/D] + a\tan[(0.5 - \epsilon)2\pi y/D]$, with $a = 1$ and $\epsilon = 0.005$, is applied to a square pupil. (*b*) The thicker line represents the $\log_{10}$ relative intensity along the diagonal line crossing the second and the fourth quadrants in (*a*). The thinner line represents the one without phase modulation. (*c*) Same as (*a*), but with phase $\phi(x, y)$ from eq. (11), with $a = 3$ and $\epsilon = 0.001$, applied to a square pupil. (*d*) Same as (*b*), but for the quadrants in (*c*). One can see that the reduction level of 10^{-12}, with an inner working distance of about $3.5\lambda_0/D$, can still be kept with a broad bandwidth of $0.6\lambda_0$ in the second quadrant.

Phase-Induced Amplitude Apodization Coronagraph (PIAAC)

Lossless apodization by aspheric optics.





Guyon, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-2006

Phase-Induced Zernike Zonal Apodization (PIZZA)

Zernike phase contrast transforms pupil phase aberration into pupil amplitude modulation.
This property is used to produce an amplitude apodization.

Martinache, 2004, J. of Opt. A, 6, 809

Lyot & Improvements on the Lyot concept

Lyot coronagraph combines pupil plane and focal plane masks to remove starlight.

Focal plane mask removes central part of PSF.
What is left (Airy rings) is mostly due to the outer parts of the pupil (the edges) -> a pupil mask (Lyot mask) removes these edges.

Well suited for solar coronagraphy
For high performance stellar coronagraphy, the original Lyot concept is limited because of a painful tradeoff between throughput, starlight rejection and inner working angle:
Higher contrast -> edges are wider -> lower throughput
Smaller IWA -> edges are wider -> lower throughput

Improvement on the Lyot concept
Part I: Amplitude masks

Apodized Pupil Lyot Coronagraph **APLC**
Soummer et al. 2003, Abe et al.
Modify (amplitude apodization) the entrance pupil to match it perfectly to the focal plane mask
Multistep APLC **APLC1, APLC2, APLC3...**
Cascade APLCs to improve the contrast / reduce Inner Working Angle

Band Limited, 4^{th} order **BL4**
Band Limited, 8^{th} order **BL8**
Kuchner & Traub, 2002; Kuchner et al., 2005
Modify (amplitude apodization) the focal plane mask to match it perfectly to the pupil. Deeper 8^{th} order null more immune to low order aberrations

Apodized Pupil Lyot Coronagraph (APLC)
= Prolate Apodized Lyot Coronagraph (PALC)

Lyot Coronagraph with apodized entrance pupil.
Prolate apodization is optimal, and can bring contrast to 1e10.
Focal plane mask is smaller than Central diffraction spot: challenging to achromatize

Output pupil (in Lyot plane) is prolate itself, and can serve as input for another Lyot coronagraph: Multistep APLC.

Adopted for Gemini Planet Imager (GPI) and Subaru HiCIAO.

Soummer et al. 2003, A&A, 397, 1161
Aime & Soummer 2004, SPIE, 5490, 456
Abe

Band-Limited mask Coronagraph (BL4, BL8)

Focal plane mask optimized to maintain fully dark central zone in pupil (band-limited mask).

4^{th} or 8^{th} order extinction.

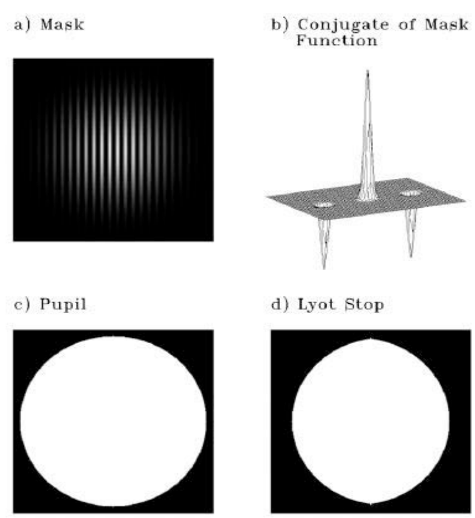


FIG. 4.—Simplest band-limited mask, analogous to a single-baseline nulling interferometer. (*a*) Mask ITF $\sin^4(x)$ multiplied by a slow taper. Dark areas are opaque. (*b*) Conjugate of the mask ATF (eq. [13]). This occulting mask can be used with any aperture shape, but for the circular aperture shown in (*c*), the corresponding Lyot stop is (*d*).

Kuchner & Traub 2002
Kuchner 2005

Improvement on the Lyot concept
Part II: Phase masks in focal plane

Phase mask **PM**
Roddier & Roddier, 1997
Smaller IWA, higher efficiency thanks to PI-shifting (ampl = -1) focal plane phase mask instead of traditional opaque (ampl = 0) mask.
Requires mild pupil amplitude apodization

4 quadrant **4QPM**
Achromatic Phase Knife Coronagraph **APKC**
Rouan et al., 2000; Abe et al., 2001
PI phase shift in 2 opposite quadrants of the focal plane, 0 phase shift in the other 2 quadrants. Less chromatic than PM.

Optical Vortex Coronagraph, topological charge m **OVCm**
Angular Groove Phase Mask Coronagraph **AGPMC**
Palacios, 2005
Phase shift is proportional to position angle in focal plane

Optical Differenciation Coronagraph **ODC**
Oti et al., 2005
Combined phase and amplitude mask in focal plane

Phase Mask Coronagraph (PM)

Lyot-like design with PI-shififting (-1 amplitude) circular focal plane mask:
- smaller mask
- smaller IWA

Requires mild prolate pupil apodization.

Phase shift needs to be achromatic
Mask size should be wavelength dependant
Dual zone PM coronagraph mitigates chromaticity

2nd order null only.

Roddier & Roddier 1997, PASP, 109, 815 (basic concept)
Guyon & Roddier 2000, SPIE, 4006, 377 (pupil apodization with PM)
Soummer et al. 2003, A&A, 397, 1161 (pupil apodization with PM)

4 Quadrant Phase Mask (4QPM)

Lyot-like design with PI-shifiting (-1 amplitude) of 2 opposize quadrants in focal plane:
- Does not require pupil apodization.
- less chromatic

Phase shift still needs to be achromatic

2nd order null only.

Used on VLT for science obs.

Rouan et al. 2000, PASP, 112, 1479

PHASE CORONAGRAPH WITH FOUR QUADRANTS. I. 1481

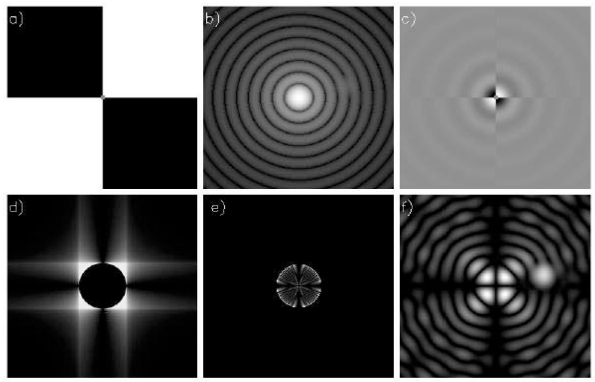


FIG. 2.—Numerical simulation illustrating the principle of the four-quadrant coronagraph. A companion 15 mag fainter (flux ratio of 10^6) is located $2.1\lambda/D$ away from the star. The individual images show (*a*) the shape of the phase mask (white for 0 phase shift, black for π phase shift), (*b*) the Airy pattern displayed in intensity, (*c*) the complex amplitude of the star phase shifted by the mask, (*d*) the exit pupil, (*e*) the exit pupil through the Lyot stop (95% of the pupil diameter), and (*f*) the coronagraphic image where the companion is clearly visible. Images are displayed with nonlinear scale.

Achromatic Phase Knife Coronagraph (APKC)

Same basic principle as 4QPM. Addresses chromaticity problem with dispersion along one axis.

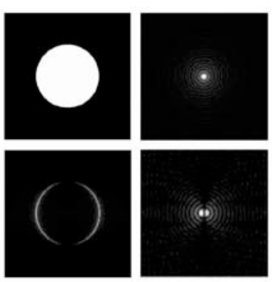


Fig. 1. Pupil intensity with perfect wavefront and its corresponding Airy pattern (*top left and right*). Intensity distribution after the Phase Knife Coronagraph has been applied (*bottom-left*): the two thin crescents encircle the pupil area perpendicular to the Knife-Edge direction. "Butterfly shape" of the point spread function of a system where half the amplitude is π-shifted in the image plane (*bottom-right*), and where a Lyot stop has been applied in the conjugate pupil plane of (*c*).

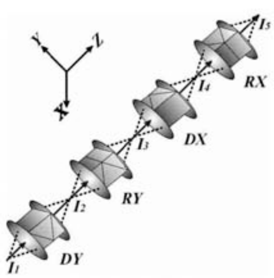


Fig. 2. Generic 3D optical scheme of the PKC. I1 is the input Airy pattern. DY is a direct vision dispersing prism in the Y direction. I2 corresponds to the first chromatic phase-knife parallel to Y. RY is a second direct-vision prism rotated by 180 degrees with respect to DY which superimposes the dispersed phase-knived airy patterns after DY. The following DX and RX operate exactly the same as DY and RY but orthogonal to them. The final coronagraphic pseudo-Airy pattern is depicted in Fig. 3 bottom-right.

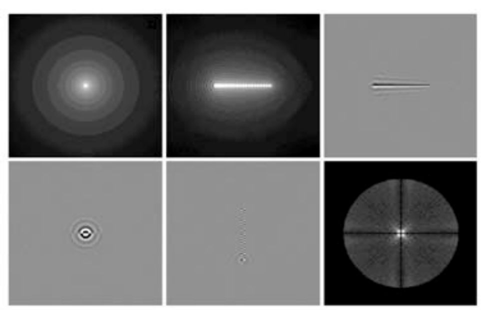
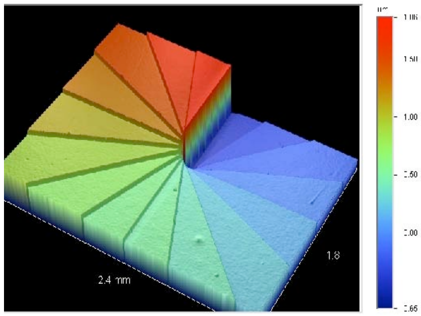


Fig. 3. Different steps of the phase-knife screen effect: (*top-left*) polychromatic Airy pattern (bandwidth: 400-800 nm) (corresponding to step I1 in Fig. 2), (*top-middle*) dispersed Airy disc, (*top-right*) the polychromatic phase-knife where the optical retardation follows the dispersion law (step I2), (*bottom-left*) an intermediate image plane where the Airy discs are de-dispersed (step I3), (*bottom-middle*) the polychromatic phase-knife applied in the perpendicular direction (step I4), (*bottom-right*) the polychromatic mutually phase-knived pseudo-Airy disc.

Abe et al. 2001, A&A, 374, 1161

Optical Vortex Coronagraph (OVC)

Phase in focal plane mask = Cst x PA



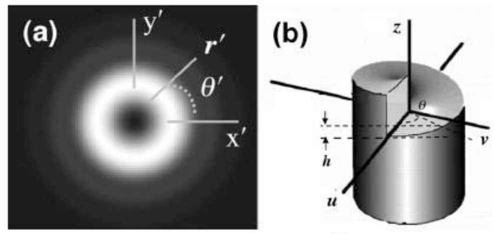


Fig. 2. (a) Intensity profile, $|U(x',y')|^2$ of a beam containing an optical vortex. (b) Surface profile of a VPM.

Palacios 2005, SPIE 5905, 196
Swartzlander 2006, Opt. Letters
Foo et al. 2005, Opt. Letters

Mawet et al. 2005, ApJ, 633, 1191
(AGPMC)

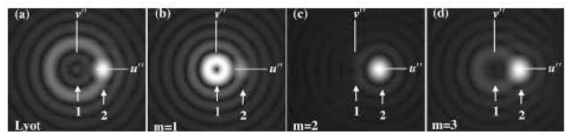
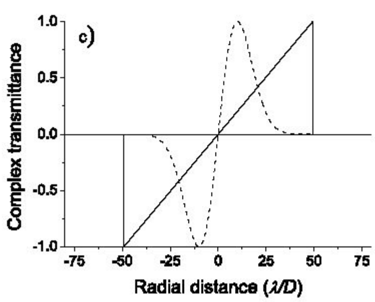


Fig. 3. Comparisons for $\alpha_2 = \alpha_{\rm diff}$ and $A_1^2/A_2^2 = 100$. (a) Lyot coronagraph where $R_{\rm OM} = r_{\rm diff}$. (b), (c), (d) Vortex coronagraphs where $m=1$, $m=2$, $m=3$, respectively. In (c) the starlight is essentially eliminated, revealing a high-contrast image of the planet when $m=2$.

Optical Differentiation Coronagraph (ODC)

Optimized version of a single axis phase knife coronagraph.



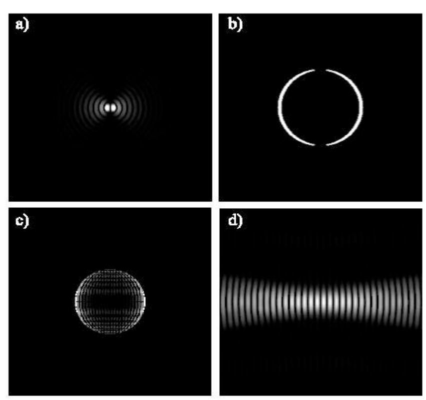
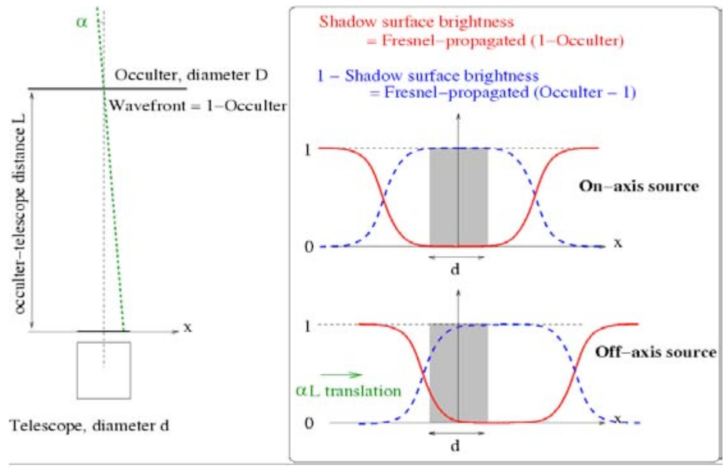


Fig. 3.—Simulated images at different planes in the optical differentiation coronagraph illustrating its principle of operation. (*a*) Image of the star PSF multiplied by the modified differentiation mask. (*b*) Intensity distribution just before (*b*) and after (*c*) the Lyot stop plane. (*d*) Final image detected at the CCD plane. Images are displayed in different intensity scales.

Oti et al., 2005, ApJ, 630, 631

External Occulter

Place large occulter far in front of the telescope:
works really well but some practical challenges...



Cash et al. 2005, SPIE, 5899, 274
Cash 2006, Nature

Removing starlight:
What are the options ???

Block light **before it enters the telescope**: create an eclipse
-> External Occulter

Remove light in the telescope, where it is most concentrated, **in the focal plane**... but this doesn't work that well: something also needs to be done in the pupil plane
-> Lyot coronagraph & improvements

Build a **nulling interferometer**
-> Interferometric coronagraphs

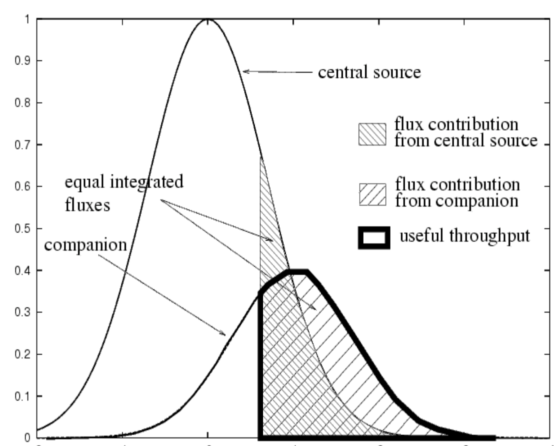
The problem is with the pupil edges: **change the pupil** to make a friendly PSF
-> pupil apodization coronagraphs

Coronagraph Performance

Defining a performance metric independant of coronagraph design

Commonly used metrics: **IWA, throughput, discovery space**

IWA: what limit ? ... 50% of max throughput ?
Throughput : how does coronagraph throughput change with separation ?
Discovery space: complex geometries ?
Overlap effects between star image and planet image.



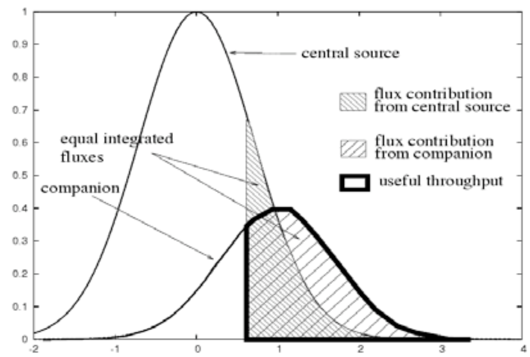
Useful throughput
fraction of the planet's light that can be isolated from the stellar light

Useful Throughput

Proposed definition:
Amount of planet light which can be isolated from stellar light.
Isolated = it is possible to gather this planet light without having gathered more starlight than planet light.
Useful Throughput is function of planet position & contrast

Measuring Useful throughput
Pixel #i has
Starlight Si
Planet light Pi

- order pixels in decreasing Pi/Si
- take first N pixels until: Sum(Si) = Sum(Pi)
- Sum(Pi) is the useful throughput



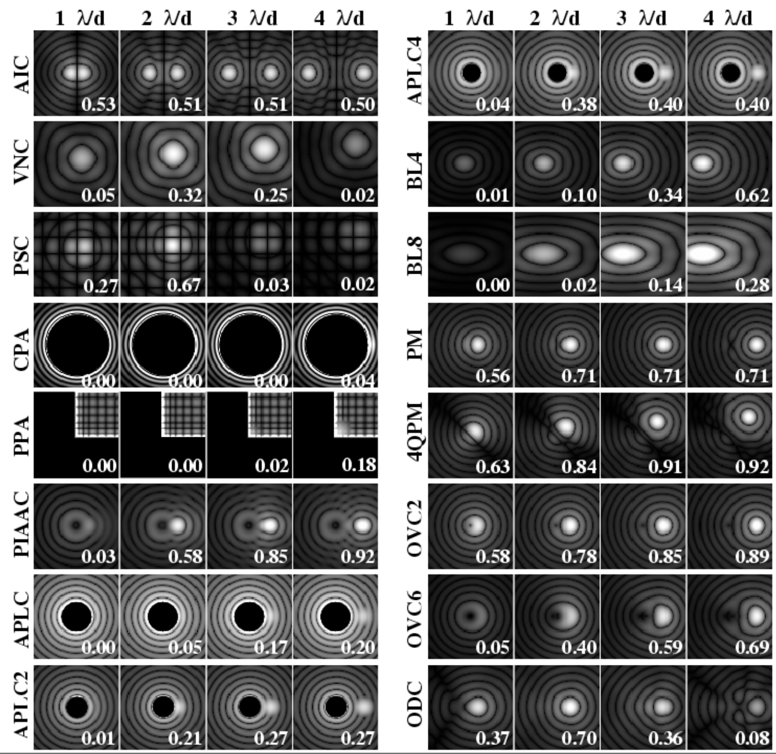
If on-axis star fully cancelled, Useful Throughput = total planet light in detector(s)

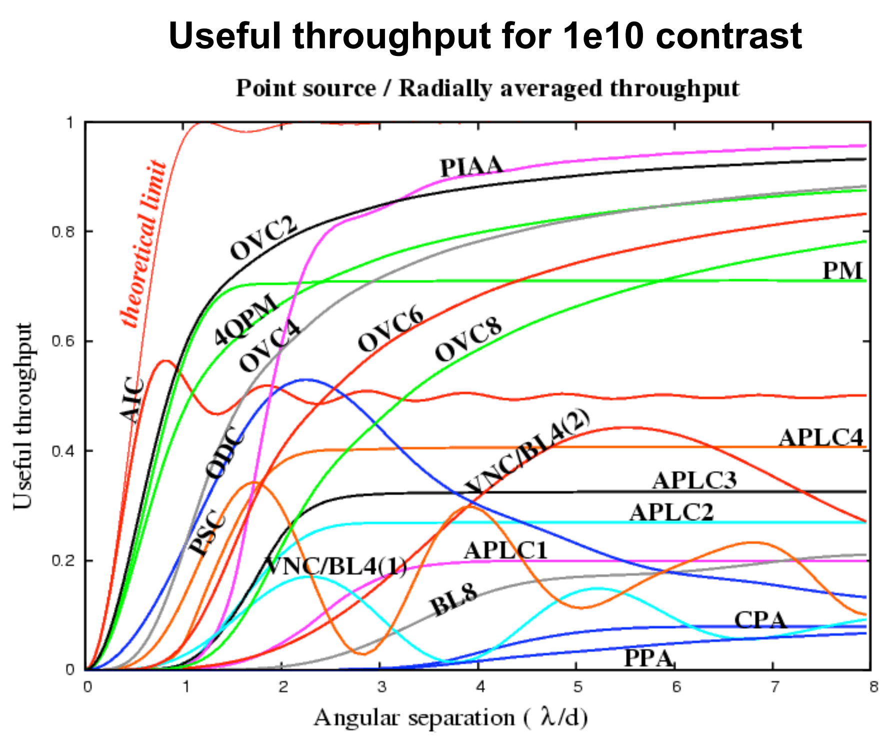
Useful Throughput

If no background, Useful Throughput is **representative of the coronagraph performance**.
Exposure time ~ prop to 1/Useful Throughput

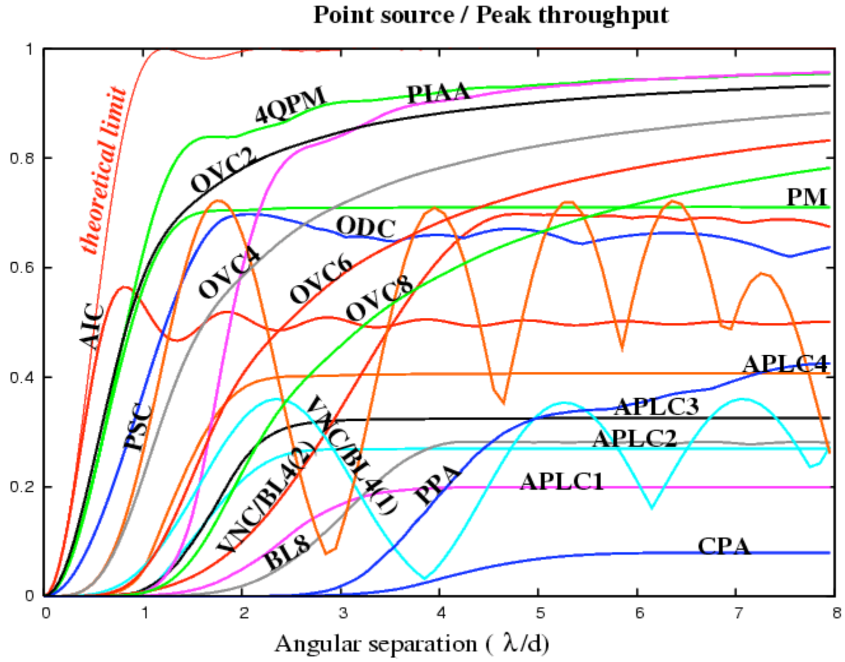
For Discovery: Radially averaged Useful Throughput
For Characterization: Peak Useful Throughput

Still somewhat a little arbitrary: can we detect planet light in much brighter stellar light ?


1 λ/d
2 λ/d
3 λ/d
4 λ/d
AIC
0.53
0.51
0.51
0.50
VNC
0.05
0.32
0.25
0.02
PSC
0.27
0.67
0.03
0.02
CPA
0.00
0.00
0.00
0.04
PPA
0.00
0.00
0.02
0.18
PIAAC
0.03
0.58
0.85
0.92
APLC
0.00
0.05
0.17
0.20
APLC2
0.01
0.21
0.27
0.27
APLC4
0.04
0.38
0.40
0.40
BL4
0.01
0.10
0.34
0.62
BL8
0.00
0.02
0.14
0.28
PM
0.56
0.71
0.71
0.71
4QPM
0.63
0.84
0.91
0.92
OVC2
0.58
0.78
0.85
0.89
OVC6
0.05
0.40
0.59
0.69
ODC
0.37
0.70
0.36
0.08


Useful throughput for 1e10 contrast
Point source / Radially averaged throughput
Useful throughput
Angular separation (λ/d)
theoretical limit
PIAA
OVC2
4QPM
OVC4
AIC
ODC
PSC
OVC6
OVC8
PM
APLC4
VNC/BL4(2)
APLC3
APLC2
APLC1
VNC/BL4(1)
BL8
CPA
PPA

Useful throughput for 1e10 contrast

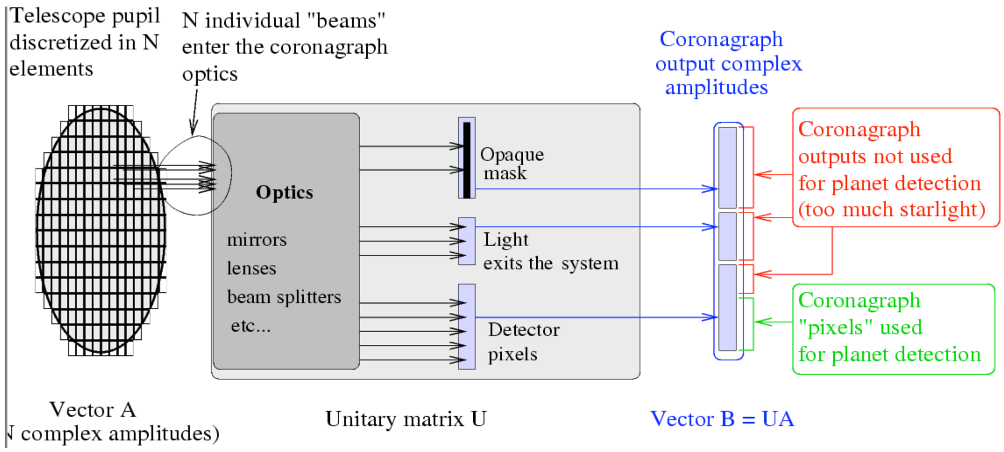


Coronagraph unified Model and Theoretical Performance Limits

Coronagraph model

Linear system in complex amplitude

Fourier transforms, Fresnel propagation, interferences, every wavefront control schemes: **all are linear**



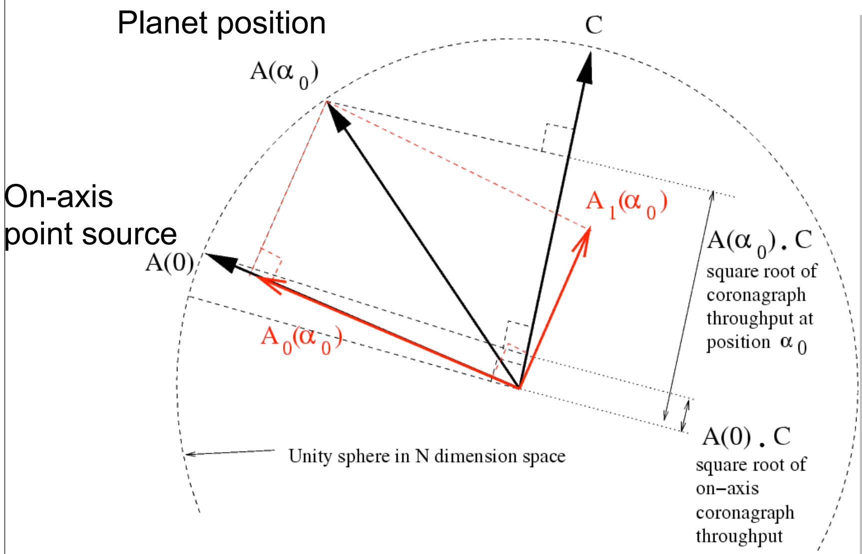
U is fixed by optical configuration, and is independant of the source position on the sky.

Coronagraph model
What is the theoretical performance limit of coronagraphy ?

Coronagraph is a linear filter which removes starlight.
If :
planet = 0.2 x starlight wavefront + **0.8 x something else**
then:
coronagraph throughput for planet < 0.8

What is the vector C that maximizes C.A(planet) but keeps C.A(star position) < C.A(planet position)*sqrt(1e-10) ?

Graphical representation of the coronagraph throughput



Coronagraph needs to remove (project) from the incident wavefront the "flat" on-axis component.
The amplitude of this component, as a function of angular separation, is by definition the ideal PSF of the optical system.

-> **Maximum theoretical throughput**
= 1 – PSF (1-Airy for circular aperture)

This conclusion is independant of how well the coronagraph needs to cancel on-axis light

Could we build this "ideal" coronagraph ?

Assume fixed planet position, previous equations yield vector C that needs to go inside matrix U. Equivalent to build coronagraph such that one output has all the light if input A = C.

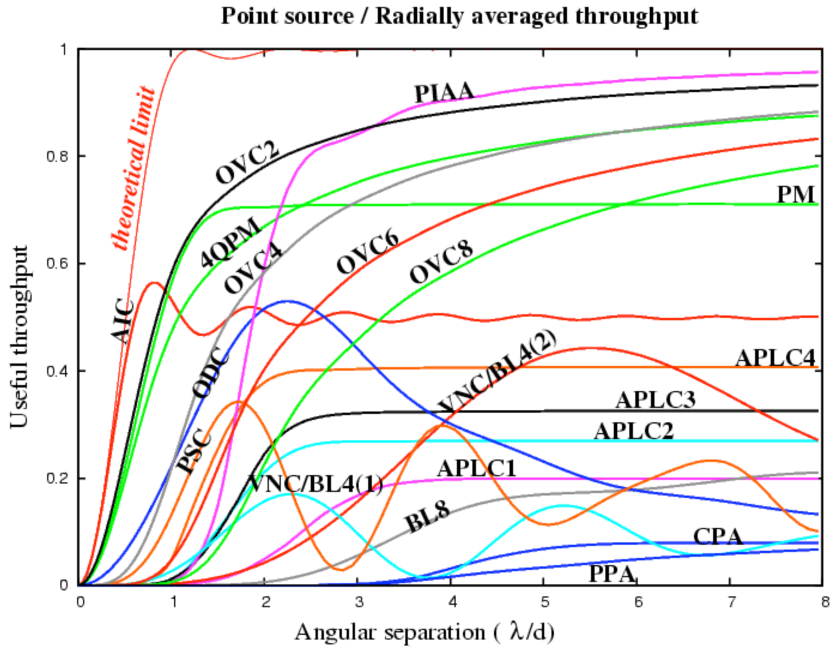
This can be done with beam splitters.
Input A=C is fully coherent, made of N individual beams.
Combine beams 1 and 2 such that all the light is is one of the 2 outputs.
Combine this output with beam 3 such that all the light is in one of the 2 outputs.
....
At the end, ALL of the light is in one "pixel"

Could we build this "ideal" coronagraph ?

Previously, we assumed fixed planet position
Can this work simultaneously for all planet positions ?

YES !
Instead of trying to build one output optimal for a given planet position, we can **concentrate ALL starlight into a single output**.
The other outputs will have no starlight (plane perp to starlight component).

Useful throughput for 1e10 contrast



What can (**will**) go wrong ?

Chromaticity ?

Sometimes very serious <u>practical</u> challenge, but it is not a fundamental limit:

- design of achromatic components
- multiple narrow bands

Stellar angular size ?

Zodi, exozodi, complex background ?

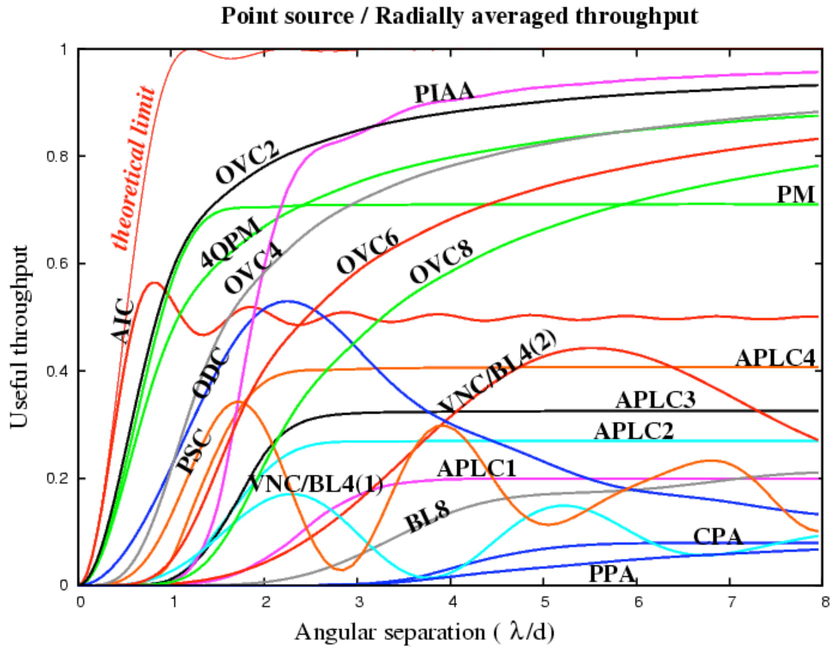
Yes, sometimes... need to minimize how much zodi/exozodi mized with planet: make PSF sharp

Stellar Size

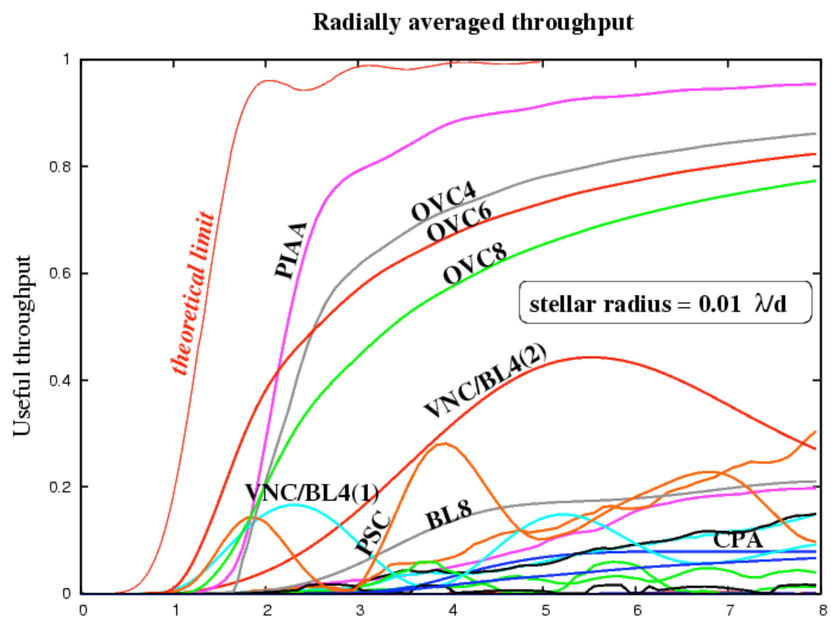
Measuring Useful Throughput with stellar size

Star is modelled as an incoherent cloud of point sources, uniformly distributed on the stellar surface.

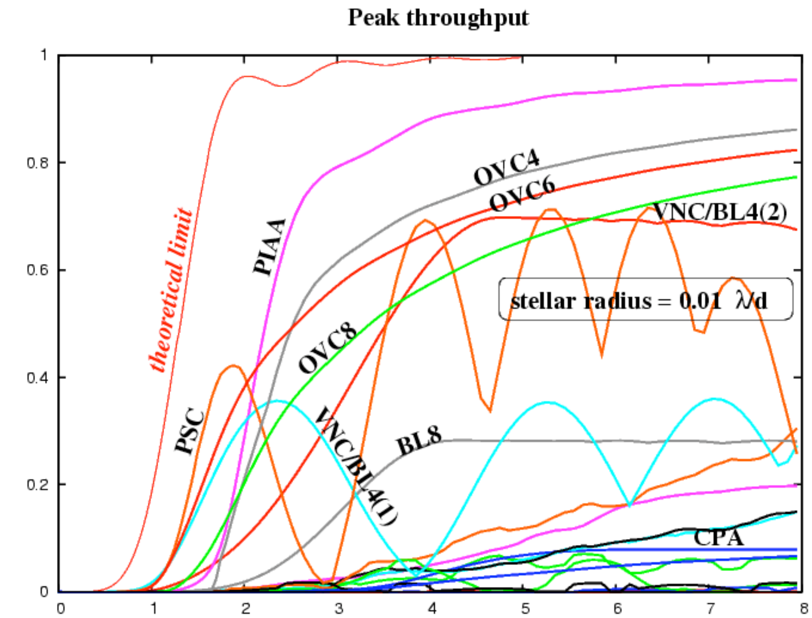
Useful throughput of existing coronagraphs



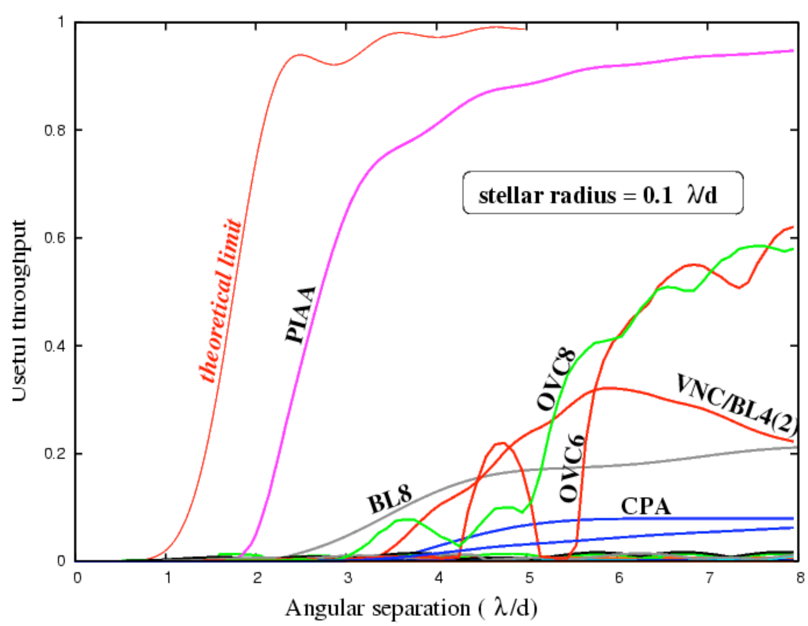
Useful throughput of existing coronagraphs



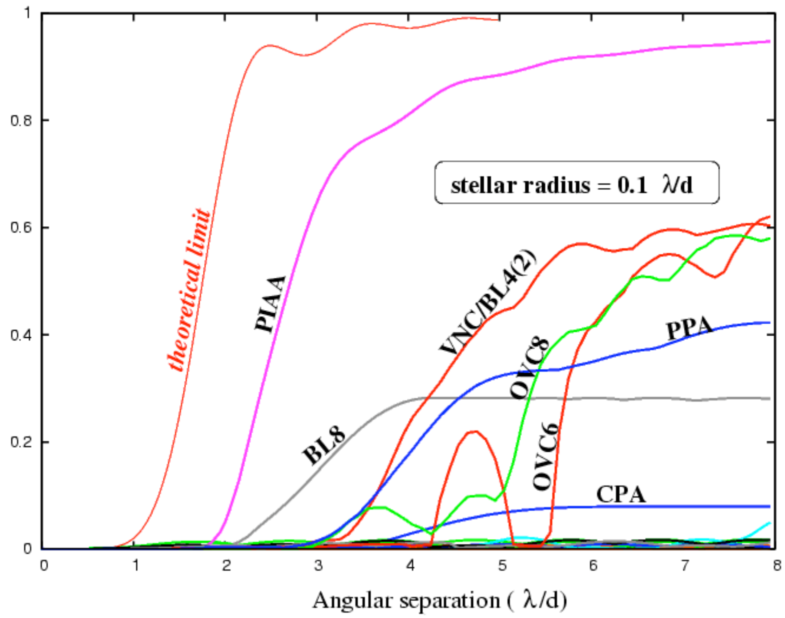
Useful throughput of existing coronagraphs



Useful throughput – average, 0.1 l/d



Useful throughput – peak, 0.1 l/d



Why is it so serious ?

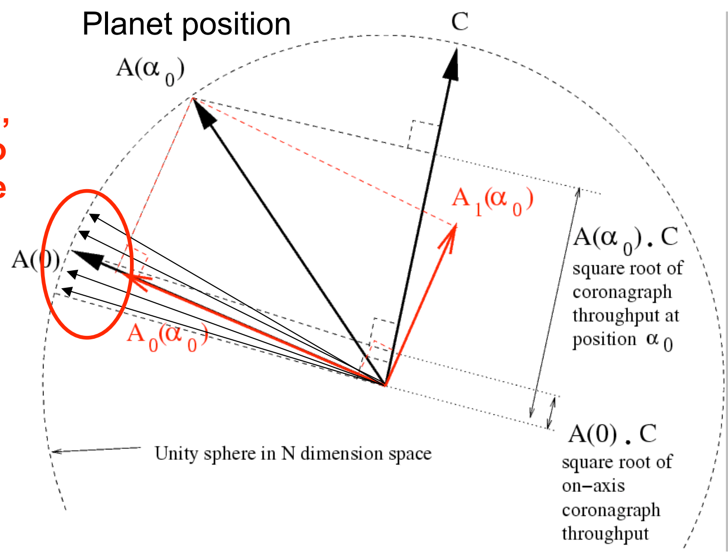
Stellar size makes light incoherent
Sun diam = 1% of Sun-Earth distance

No hope of fixing this by wavefront control, the coronagraph has to deal with it !

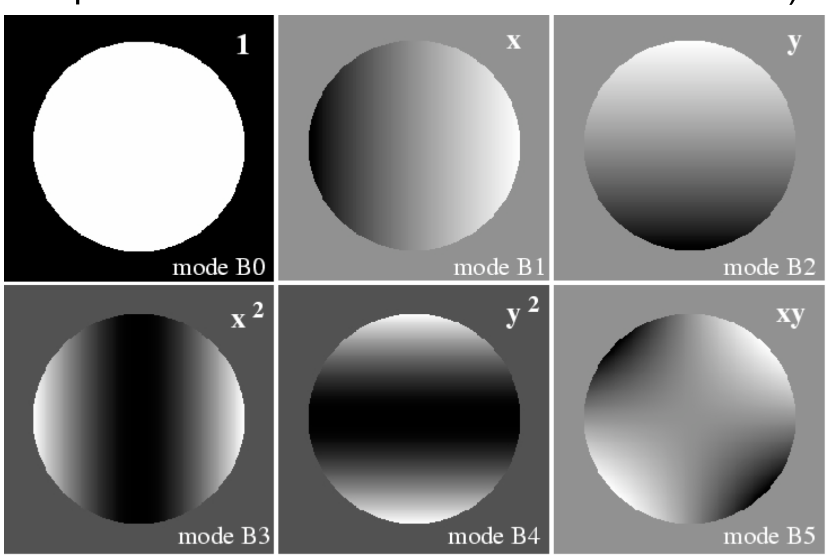
In a stellar size limited coronagraph, remaining speckles have opposite complex amplitude from one side of the star to the other. Adding complex amplitude can only increase intensity.

Graphical representation of the coronagraph throughput

Central star is made of a group of vectors, ALL of which need to be cancelled to some degree.



Need to remove more than 1 mode from the incoming wavefront (how many and how well depends on the star size and desired contrast)



Theoretical limit with increasing stellar radius (monochromatic light)

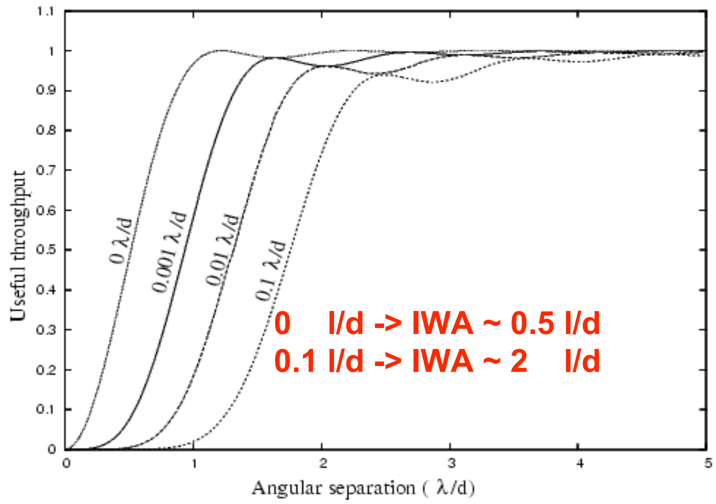
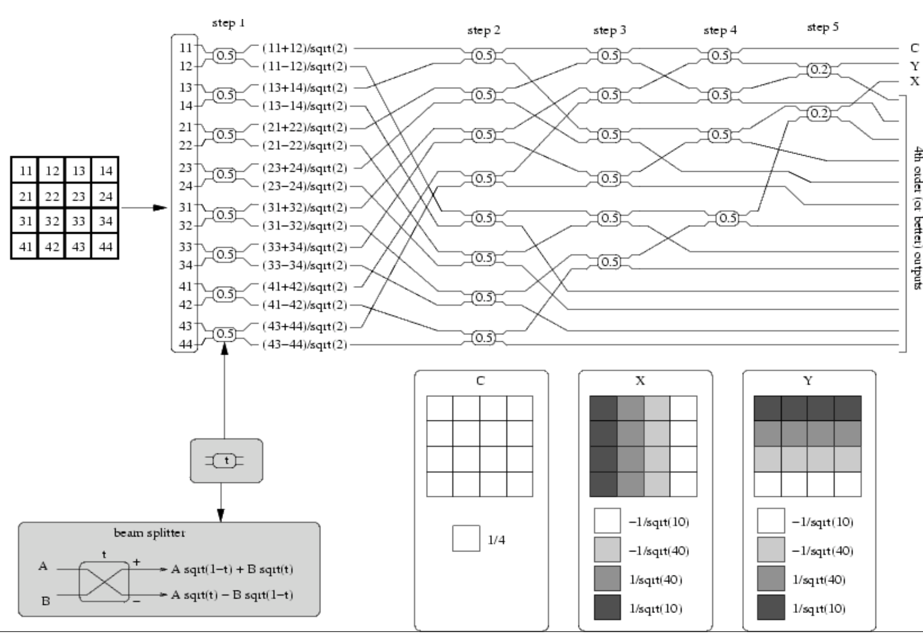
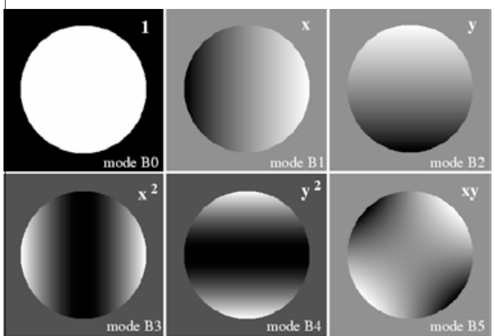


Fig. 5.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

An "ideal" coronagraph for extended source with discrete beam splitters



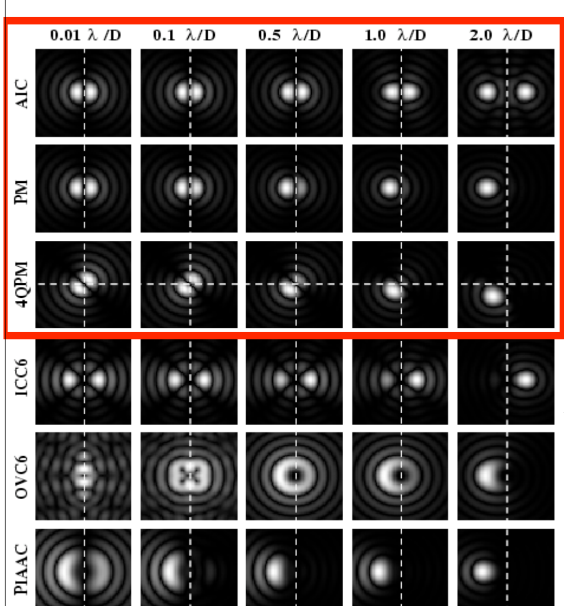
modes removed linked to null depth and predicts coronagraph behaviour at small angular separation



2nd order null: only B0 removed
at small angular separation, B1 and B2 dominate, and their amplitude is prop to separation

Predictions:
As source moves away, PSF does not change, but its intensity is prop to square of separation
180 deg ambiguity in image

Coronagraphic PSFs at small angular separation



2nd order null

6 modes removed
x^3, y^3, xy^2, x^2y dominate

More complex interractions between modes

Zodi / Exozodi

Zodi & exozodi

With "good" coronagraph (small sharp PSF), planet likely to stand out of the background (zodi+exozodi) for nearby system.

What makes things worse:

- distance to system
- increasing lambda
- poor angular resolution
- complex PSF structure (multiple peaks, diffraction in some directions ...)

Coronagraph design

Diffractive Efficiency Factor (DEF):
how much more background light is mixed to the planet's PSF than in the simple non-coronagraphic telescope case (Airy + background).

The ultimate coronagraph dream:

Can we ...

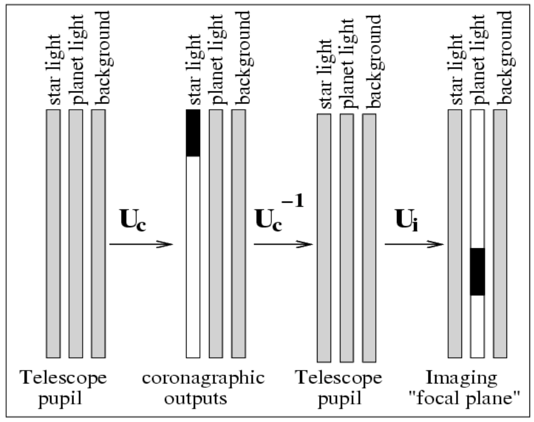
Reach the perfect limit for source size > 0
AND
have diffractive efficiency factor (DEF) = 1 ?

By the way, it would be nice if it were optically simple

Yes, it is possible !

But no optically simple implementation known

(lots of beam splitters)

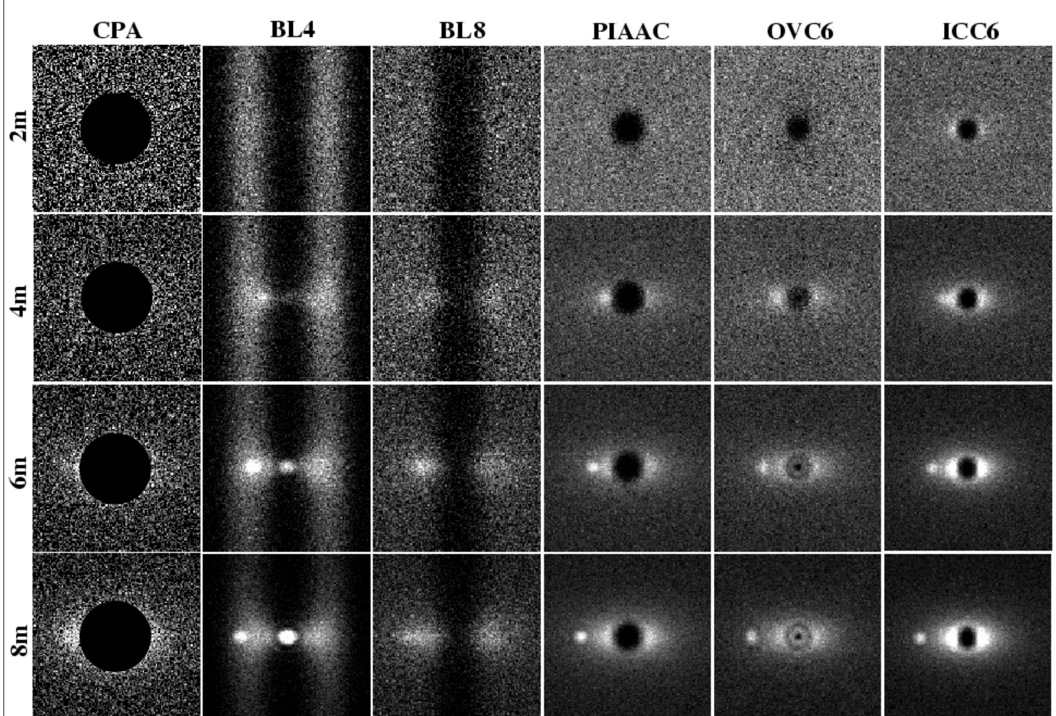


Numerical Simulations for Exo-Earths imaging

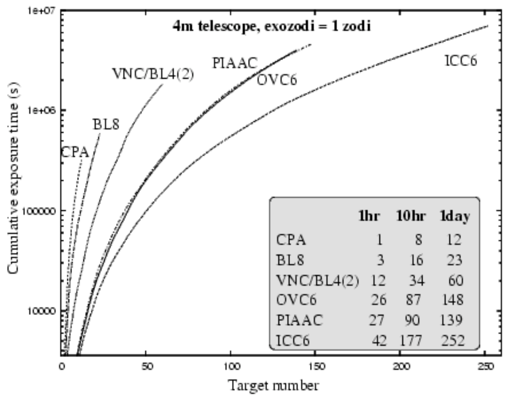
Example:
HIP 56997 (G8 star at 9.54pc)
0.55 micron, 0.1 micron band
Planet at maximum elongation (80 mas)
Earth albedo = 0.3 (C=6e9)
4h exposure, 0.25 throughput, perfect detector

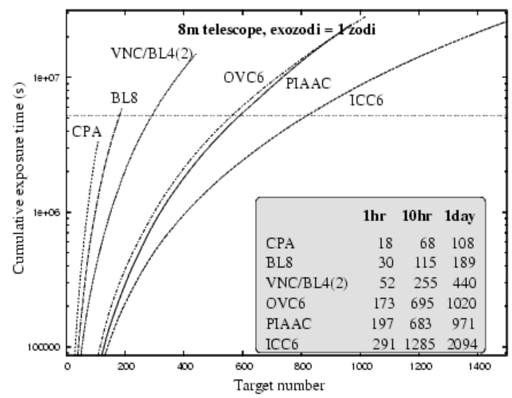
Exozodi : 1 zodi
System observed at time when zodi is minimal

Each image is 20x20 lambda/d



1 zodi, 50% detection at SNR = 7





In 8m plot (right), line = 2 months open shutter time
with 6 visits per target, 1 year, excluding overhead (pointing)
-> number of targets limited by mission life

Side benefits of high performance coronagraph

(1) High throughput enables high contrast
- more photons for wavefront control: makes it easier to cath up with non-predictible drifts & vibrations

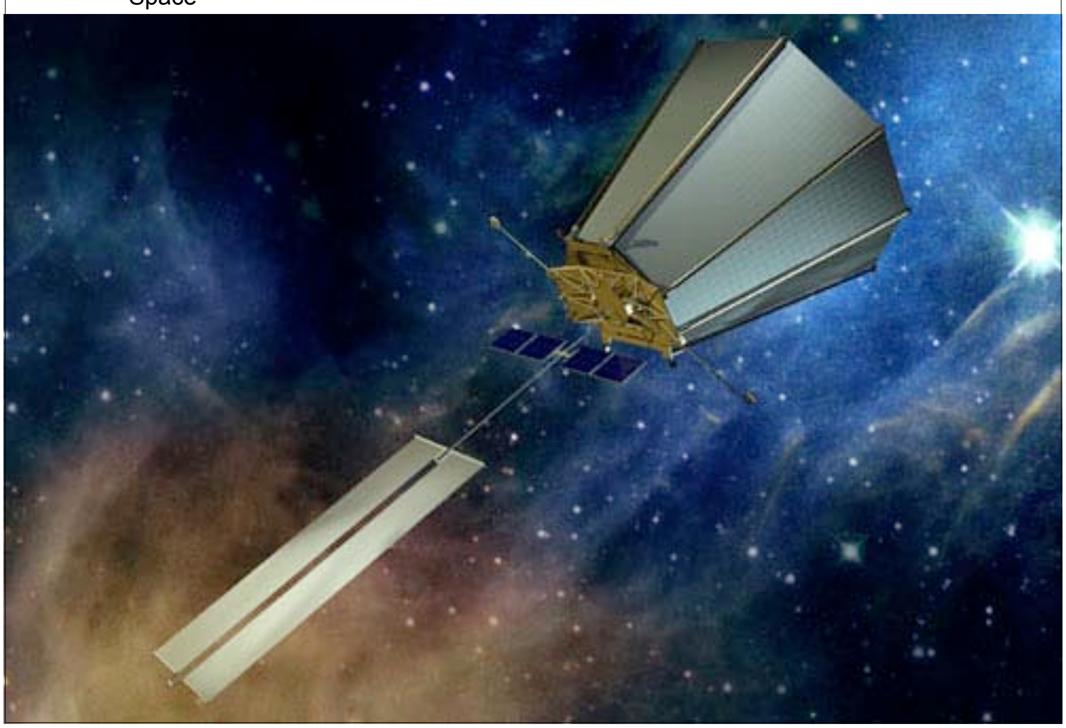
(2) High throughput + good angular resolution reduces need for revisits
- for closeby objects, proper motion confirmation < day
- less confusion with exozodi clumps and/or other planets

(3) Short exposure time per visit: high overheads

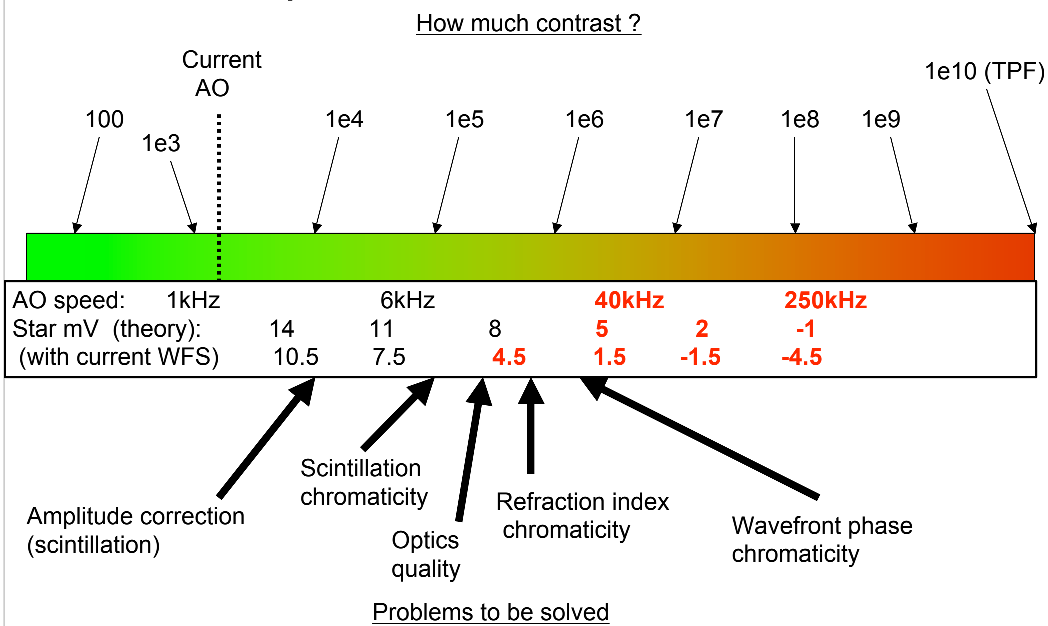
(2)+(3) : more characterization for initial visits ?

Wavefront Control

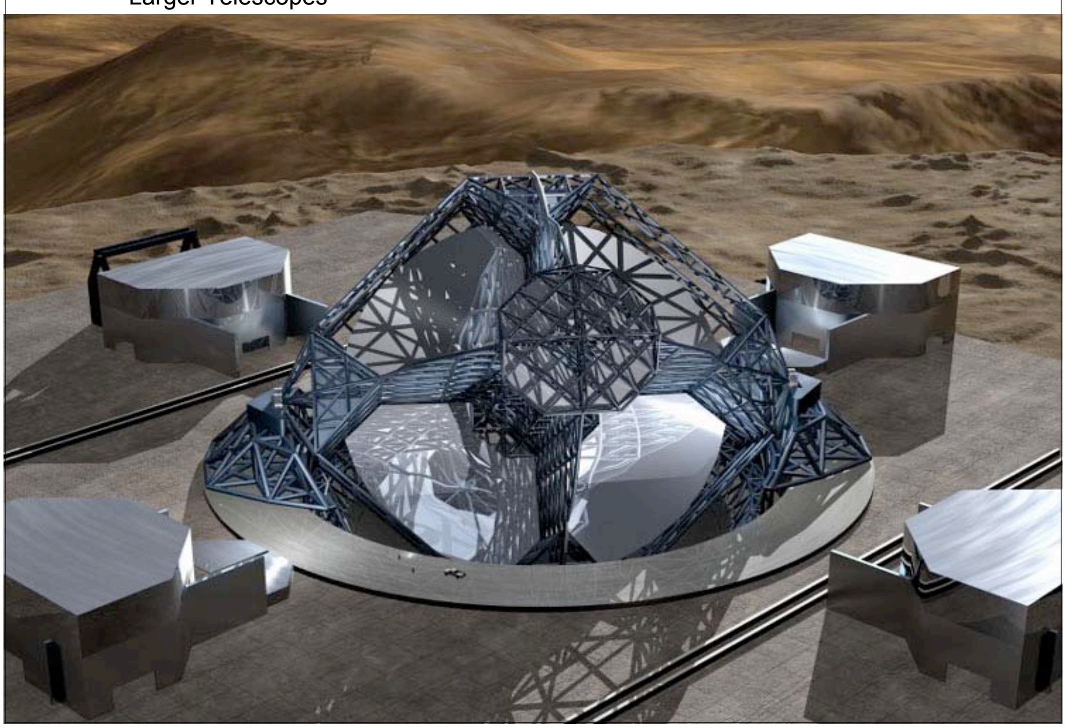
Space



Extreme-AO from the ground: raw contrast at 0.5” with 8m telescope



Larger Telescopes



Wavefront Control on coronagraphs

Wavefront (optics/atmosphere) not expected to be rock steady on large pupil.

Need to **simultaneously** answer 2 questions:
(1) How much wavefront aberration is acceptable ?
Open-loop wavefront sensitivity
(2) How well can it be corrected (= how well can it be detected = how rapidly can it be sensed vs. How fast does it change) ?
Wavefront sensing efficiency

Together, these 2 answers will set the open loop **wavefront stability requirement**

Low-order aberrations

Low IWA coronagraphs require smaller low-order aberration (especially true for tip-tilt).
Stellar angular size = tip-tilt !!
Stellar angular size analysis can be generalized to low order aberrations & help match coronagraph design with wavefront errors

Larger IWA coronagraphs (CPA for example), tolerate larger aberrations but **cannot detect them unless they are large.**

We can always expect low-order aberrations to be at the level where they start to impact contrast at the IWA.
UNLESS... we use the light on the focal plane occulter

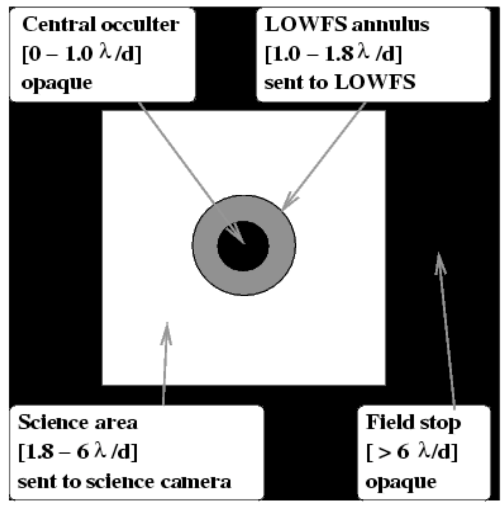
Example of a Dedicated Low-Order Wavefront Sensor (LOWFS)

Use "for free" light from central star

This example will work for:

- CPA
- BL4, BL8
- PIAA
- APLCs

Same general principle can be applied to other coronagraphs (PM, 4QPM, OVC)



Dedicated Low-Order Wavefront Sensor (LOWFS)

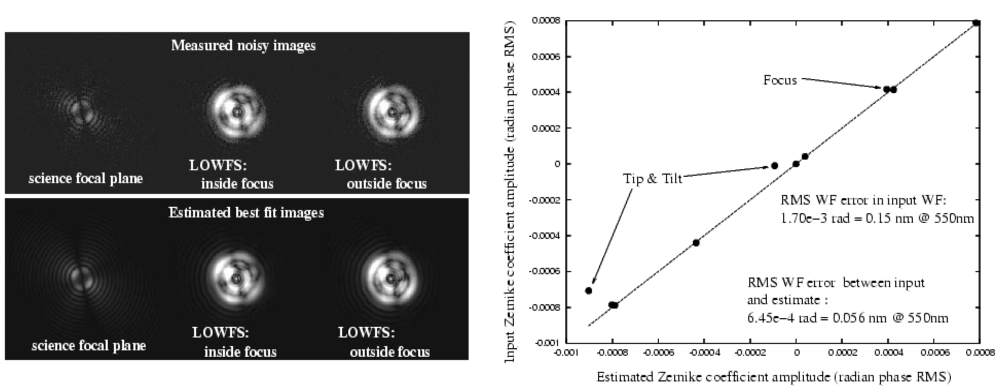


Figure 6. Noisy inside and outside focus images obtained by the LOWFS (top left). Photon noise is included in this simulation, where 10^{12} photons entered the telescope pupil. These images were simulated at 550nm with a 50pm error per Zernike for the first 10 Zernikes. Wavefront reconstruction from these 2 frames accurately recovers low order wavefront aberrations (right), to an accuracy level which exceeds the requirement for 10^{10} contrast. Simulated science focal plane and LOWFS (bottom left), computed from the wavefront estimation, match the noisy images acquired by the LOWFS (top left).

Deriving Wavefront stability requirements (example: TOPS, 1.2m telescope with PIAA)

Table 1. Wavefront control requirements for 10^{10} contrast. Wavefront tolerances are given at the entrance of the PIAA. A coronagraph system including PIAA, focal plane occulter and inverse PIAA was simulated at 550 nm to derive these requirements. The sampling time necessary to measure the corresponding level of aberration at SNR=5 is given here for a $m_V = 5$ star.

Mode	Required control accuracy	Sensor	SNR=5 sampling time
Tip / tilt	0.9 nm rms/mode	LOWFS	0.5 s
Focus	43 pm rms	LOWFS	1 s
Astigmatism	70 pm rms/mode	LOWFS	1 s
Mid spatial frequencies	1.5 pm rms/mode [≈40 pm rms total, 15 pm per actuator]	Science CCDs & LOWFS	5 min
High spatial frequencies	Strehl ratio > 0.98	none, relies on optical quality of components	-

Tip/Tilt stable to 0.9nm within ~5 s
Focus stable to 43 pm within ~10 s
Mid Spatial frequ stable to 1.5 pm within ~50 min
(assuming correction bandwidth = 0.1 sampling bandwidth - PESSIMISTIC)

Deriving Wavefront stability requirements

1.2m telescope / 1e10 contrast:
Tip/Tilt stable to 0.9nm within ~5 s
Focus stable to 43 pm within ~10 s
Mid Spatial frequ stable to 1.5 pm within ~50 min

Bigger telescope:
- + faster sensing (more photons) – sampling time ~ 1/D^2
  - 4m telescope: 11 times faster (50 min -> 4.5 min)
- \- input wavefront less stable

Lower throughput / larger IWA coronagraph
- \- slower sensing
- + more tolerant to low-order aberrations

Conclusions

- In last few years, many coronagraph concepts have been proposed and studied. Several of them are being tested in the lab and/or on telescopes.
Direct imaging of exoEarths looks especially attractive and within reach of ~2m visible space telescope

- stellar size and low order aberrations are very important and fundamental limitation (loss of coherence) – especially critical when trying to go to small separations.

- Theoretical limits identified but not (yet) practical to build. There is still room for improvement, but not huge improvement (Max gain = factor 2 in # of accessible terrestrial planets).

More info...

Coronagraph Theory :
Guyon, Pluzhnik, Kuchner, Collins, Ridgway, ApJ Supp. 167, 81, 2006

Coronagraph designs :
Tuesday afternoon “Coronagraph Theory & Innovation”

Wavefront Control :
Wednesday morning “Wavefront control, Observing techniques and methods”

email: guyon@naoj.org