Observing Exoplanets

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My Background

Astronomer / Optical scientist at University of Arizona and Subaru Telescope (National Astronomical Observatory of Japan, Telescope located in Hawaii)

I develop instrumentation to find and study exoplanet, for ground-based telescopes and space missions

My interest is focused on habitable planets and search for life outside our solar system

At Subaru Telescope, I lead the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument.
ALL known Planets until 1989
Approximately 10% of stars have a potentially habitable planet

200 billion stars in our galaxy

\[ \rightarrow \text{approximately 20 billion habitable planets} \]

Imagine 200 explorers, each spending 20s on each habitable planet, 24hr a day, 7 days a week.

It would take \( >60 \text{yr} \) to explore all habitable planets in our galaxy alone.

\[ \times 100,000,000,000 \text{ galaxies in the observable universe} \]
Habitable planets

Potentially habitable planet:
- **Planet mass** sufficiently large to retain atmosphere, but sufficiently low to avoid becoming gaseous giant
- **Planet distance to star** allows surface temperature suitable for liquid water (habitable zone)

**Habitable zone** = zone within which Earth-like planet could harbor life
Location of habitable zone is function of star luminosity $L$. For constant stellar flux, distance to star scales as $L^{1/2}$

Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star)

Proxima Centauri (M type star)
Habitable planets

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Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star):
18 solar mass

Proxima Centauri (M type star):
0.123 solar mass
Habitable planets

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*Habitable zone = zone within which Earth-like planet could harbor life*
Location of habitable zone is function of star luminosity $L$. For constant stellar flux, distance to star scales as $L^{1/2}$

Examples:

Sun
→ habitable zone is at $\sim 1$ AU

Rigel (B type star):
18 solar mass
100000x Sun luminosity

Proxima Centauri (M type star):
0.123 solar mass
1/600 Sun luminosity
Habitable planets

Potentially habitable planet:
- **Planet mass** sufficiently large to retain atmosphere, but sufficiently low to avoid becoming gaseous giant
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**Habitable zone = zone within which Earth-like planet could harbor life**
Location of habitable zone is function of star luminosity $L$. For constant stellar flux, distance to star scales as $L^{1/2}$

Examples:

Sun
→ habitable zone is at ~1 AU

Rigel (B type star):
18 solar mass
100000x Sun luminosity
→ habitable zone is at ~300 AU

Proxima Centauri (M type star):
0.123 solar mass
1/600 Sun luminosity
→ habitable zone is at ~0.04 AU
How to identify exoplanets?

HIGH PRECISION OPTICAL MEASUREMENTS OF STARLIGHT (indirect techniques)

Earth around Sun at ~30 light year

→ **Astrometry**: measure star position
moves by 0.3 micro arcsecond
(thickness of a human hair at 20,000 miles)

→ **Radial velocity**: measure speed along line of sight
Star velocity is modulated by 10cm/sec
(changes light frequency by 1 part in 3,000,000,000)

**Transit**: measure star brightness
If Earth-like planet passes in front of Sun-like star, star dims by 70 parts per million
(12x12 pixel going dark on a HD TV screen 70 miles away)
Exoplanet transit
If the planet passes in front of its star, we see the star dimming slightly

Transit of Venus, June 2012
Habitable Zones within 5 pc (16 ly):
Astrometry and RV Signal Amplitudes for Earth Analogs

Circle diameter is proportional to 1/distance
Circle color indicates stellar temperature (see scale right of figure)
Astrometry and RV amplitudes are given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

Expected detection limit for space astrometry (NEAT, THEIA, STEP) F, G, K stars

Expected detection limit for near-IR RV surveys (SPIROU, IRD + others) M-type stars
Spectroscopy of Earth-like planets
... allows detection of biomarkers

Spectroscopy can identify biomarkers: molecular species, or combinations of species that can only be explained by biological activity
On Earth: water + O$_2$ + O$_3$ + CH$_4$
Spectra of Earth obtained through Earthshine observation also reveals vegetation's red edge!

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**Turnbull et al. 2006**

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**Fig. 7.**—Earth’s observed reflectance spectrum, at visible and near-infrared wavelengths, created from a composite of the data in this paper (0.8–2.4 μm) and the data presented in Paper 1 (0.5–0.8 μm). The strongest molecular signatures are indicated, as are the wavelengths where Rayleigh scattering and vegetation reflection are most significant.
Direct imaging of Exoplanets (incl. Habitable planets) measures ...

- Orbit
- Atmosphere composition
- Continents vs. Oceans?
- Rotation period
- Weather patterns
- Planetary environment: Planets + dust
**Exoplanets imaging**

**angular separation, contrast: why is it difficult?**

*What would our solar system look like from 10pc away?*

- Sun would be $m_V = 4.8$ star (faint naked-eye star)
- Sun diameter would be 0.001” (diffraction limit of a 200m telescope in the near-IR)
- Sun-Earth separation would be 0.1” (diffraction limit of a 2-3m telescope in the near-IR)
- Earth diameter = 0.00001” (diffraction limit of a 20km diameter telescope in near-IR)
- In the visible:
  - Earth at $1e-10$ contrast would be $m_V \sim 30$ sources (very faint, would be challenging even for Hubble without the host star)
  - Jupiter in the visible would be $\sim 10x$ brighter than Earth, at 0.5”
  - Zodiacal light would be several 100x brighter than Earth when integrated, and brightest near Sun
- In the near IR (\~2 um): similar contrasts
- In the thermal IR (\~10 um):
  - Contrasts are much more favorable
  - Earth is brightest planet, at $\sim 1e-6$ contrast
Taking images of habitable exoplanets: Why is it hard?
Habitable Zones within 5 pc (16 ly)

Circle diameter indicates angular size of habitable zone
Circle color indicates stellar temperature (see scale right of figure)
Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)

1. Gliese 1245 A
2. Gliese 1245 B
3. Gliese 674
4. Gliese 440 (white dwarf)
5. Gliese 876 (massive planets in/near HZ)
6. Gliese 1002
7. Gliese 3618
8. Gliese 412 A
9. Gliese 412 B
10. AD Leonis
11. Gliese 832

Contrast is given for an Earth analog receiving the same stellar flux as Earth receives from Sun (reflected light)
Exoplanets: Contrast ratio, visible vs. infrared

In the visible, planets are very faint unless they are very close to their star (luminosity goes as $d^{-2}$). Planets in or near habitable zone cannot be imaged from the ground, and would require dedicated space telescope+instrument.

In the near-IR, giant and young planets ("young Jupiters") can be imaged:
- AO systems work well in the near-IR
- Giant planets emit their own light (thermal emission)
- Young planets are still very hot, and slowly cool after formation

In the Thermal IR (~10 um & longer), contrast is even more favorable, and older giant planets can be imaged (this is one of the key science goals of JWST)

2M1207 exoplanet (Chauvin et al., ESO, 2004)
Probably the first direct image of an exoplanet

HR8799: first image of exoplanetary system with multiple planets (Marois et al. 2009)
Exoplanets & dust disks

Protoplanetary disk: Disk in the process of forming planets

Debris disk: Disk generated by collision between small bodies

Ability to image planets and disks → study planetary formation and evolution of planetary systems

Beta Pic exoplanet and dust disk (Lagrange et al. 2009)
Kalas et al., HST image
Coronagraphy
Why coronagraphy?

Conventional imaging systems are not suitable for high contrast (even if perfect) due to diffraction.
Why do we need coronagraphs?

Coronagraph can only remove known & static diffraction pattern

**BUT:**
- static & known diffraction can be removed in the computer
- coronagraphs don’t remove speckles due to WF errors

**Fundamental reasons:**
1. Photon Noise
2. Coherent amplification between speckles and diffraction pattern

**Practical reasons:**
3. Avoid detector saturation / bleeding
4. Limit scattering in optics -> “stop light as soon as you can”
Coherent amplification between speckles and diffraction pattern

Final image = PSF diffraction (Airy) + speckle halo

This equation is true in complex amplitude, not in intensity. Intensity image will have product term -> speckles are amplified by the PSF diffraction.

Aime & Soummer 2004
**Coherent amplification between speckles and diffraction pattern**

Final image = PSF diffraction (Airy) + speckle halo

\[
\text{Image} = |A_{\text{PSF}} + A_{\text{speckles}}|^2
\]
\[
= |A_{\text{PSF}}|^2 + |A_{\text{speckles}}|^2 + 2 |A_{\text{PSF}}| |A_{\text{speckle}}| \cos(\theta)
\]

With PSF >> Speckles, this term dominates speckles
Coronagraph concepts & systems

Types of coronagraphs

Coronagraph systems & instruments

Olivier's thumb...
the simplest coronagraph
Doesn't work well enough to see planets around other stars

**Coronagraphs for imaging exoplanets are based on diffractive optics, not geometrical optics**
What is light: particle or wave?

1807: Thomas Young publishes his double-slit experiment result … cannot be explained by Newton's corpuscular theory of light

1818: French academy of science committee launches a competition to explain nature of light

Augustin-Jean Fresnel submits wave theory of light

Simeon-Denis Poisson finds a flaw in Fresnel's theory: According to Fresnel's equations, a bright spot should appear in the shadow of a circular obstacle → this absurd result disproves Fresnel's theory

Dominique-Francois-Jean Arago, head of the committee, performs the experiment. He finds the predicted spot → Fresnel wins the competition
Water waves diffract around obstacles, edges, and so does light

→ designing a coronagraph is more complicated than simply putting an opaque mask at the star location in an image
Types of Coronagraphs

3 main approaches to remove starlight:

- Block starlight BEFORE it enters the telescope using a large **external occulter** $\sim 50000$ km in front of the telescope

- Design masks and optical components inside the telescope to induce starlight destructive interference at the expected location of a planet in the image: **internal coronagraph**

- Induce destructive interference between beams of multiple telescopes: **nulling interferometer**
Internal Coronagraphs: main approaches

Beam splitting and destructive interference

Apodization

Phase masks in focal plane

Amplitude masks in focal plane
High Contrast Imaging systems
What is a high contrast imaging system (ground or space)?

*Imaging system optimized to provide high contrast at small angular separation.*

Key elements:

- **Coronagraph** or nulling interferometer to optically remove starlight and isolate planet light (overcomes diffraction)

- **Wavefront correction system** to reduce and calibrate residual wavefront errors
  - For coronagraphs: Extreme-AO system to flatten wavefront
  - For interferometers: Optical pathlength sensing / correction (+ AO on individual apertures of the interferometer)

- **Science detector (+ differential detection technique)** for imaging, spectroscopy and polarimetry
  - (note: the science detector can be part of the wavefront control system, and measure residual scattered light to be removed)
From conventional AO to Coronagraphic Extreme-AO

We use a non-extreme AO system image as starting point. Example of a very good PSF with a current AO system: LBT AO image.

- PSF diffraction (Airy rings, spiders) REMOVED BY CORONAGRAPHER
- Static and slow speckles MUST BE REMOVED BY CALIBRATION SYSTEM OR DIFFERENTIAL IMAGING (actively or in post processing)
- Control radius of AO DEFINED BY NUMBER OF ACTUATORS IN DM: MAY BE INCREASED WITH MORE ACTUATORS IF REQUIRED
- Residual atmospheric speckle halo REDUCED BY FAST, ACCURATE AND EFFICIENT AO SYSTEM
1: ExAO control radius
2: Telescope spider diffraction
3: Diffraction rings
4: Ghost spider diffraction
5: “butterfly” wind effect
6: Coronagraphic leak (low order aberrations)

Monochromatic PSFs, 1.65um
No photon noise
10m/s wind speed, single layer
4ms wavefront control lag

No AO correction
Extreme-AO correction
Extreme-AO + coronagraph
Coronagraphs reduce speckle noise

“speckle pinning” effect

**PSF subtraction residual (no photon noise)**

Difference between two PSFs, exposure time per PSF=100 coherence times

**ExAO**

**ExAO + coronagraph**

Control radius = 0.83 arcsec

![Graph showing contrast variance vs. angular separation](chart.png)

Angular separation [λ/D]

-3 -3.5 -4 -4.5 -5 -5.5 -6

0 5 10 15 20 25 30
Current and future high contrast systems - ground

**Subaru Coronagraphic Extreme AO** – under operation and development
- Small inner working angle **PIAA coronagraph**
- Pointing sensing and control with **coronagraphic low order WFS**
- **Speckle control** using focal plane image as sensor
- **2000-element deformable mirror**
- Includes **Integral Field Spectrograph** to help remove speckles and acquire spectra

**Gemini Planet Imager (GPI)** – **large survey** starts observations in 2014
- ExAO system using 64x64 MEMS DM + coronagraph
- Includes **calibration interferometer** to accurately measure residual speckles
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra

**ESO’s SPHERE on VLT** – **large survey** starts observations in 2014
- ExAO system + coronagraph
- Highly stable bench
- Includes Integral Field Spectrograph to help remove speckles and acquire spectra
- Includes **differential polarimetric imager**

**MagAO-X** – under development for 6.5m Magellan Telescope
- High speed, high efficiency ExAO system, visible light optimized, **2000 elements**
- Small IWA coronagraph (PIAACMC + other modes)
Current and future high contrast systems - ground

Gemini Planet Imager

SPHERE (European Southern Observatory)

PALM3000/P1640 (Palomar 5-m Telescope)

PALM3000 installed at the Casse focus of the Hale Telescope at Palomar Mountain. Photo: Scott Kardel

Subaru Coronagraphic Extreme-AO
Subaru Coronagraphic Extreme Adaptive Optics
Fiber-fed instruments (not visible here):
- RHEA (visible IFU, R=70,000)
- IRD (near-IR spectrograph, R=70,000)
  + experimental photonics spectro
SCExAO Light path

Facility AO

Active WF correction
Dedicated science instrument
Mixed science/WFS

Dedicated WFS
Visitor port
\textit{dichroic}
\textit{beam switch}

SCExAO Light path

2-5um IFU

Weakly/un-modulated Visible PyWFS 0.6-1.0 \text{ um}

111 DM segmented

FIRST Polarimetry Interferometry

coronagraphic LOWFS

IRD 1-2 \text{ um HR spectrograph}

Photonic nuller

IRDS

MKIDS focal plane WFS

SAPHIRA Imager

VAMPIRES (2 cameras)
Polarimetry Dual band Aperture masking

BEAM SWITCHER

ADC 1 Hz

64x64 DM 2 \text{ kHz}

50x50 DM 3.5 \text{ kHz}

Coronagraph

Modulated Visible PyWFS 0.4-1.0 \text{ um}

Weakly/un-modulated NearIR PyWFS 0.8-2.0 \text{ um}

2-5um imager/spectro (IRCS)
Current PSF stability @ SCExAO

Stable PSF for coronagraphy
SCExAO provides sensing and correction at 500 Hz - 3.5 kHz
14,400 pixel WFS → 2000 actuators

1630nm (SCExAO internal camera)
3 Hz sampling
Relationship between speckle and wavefront errors

pupil plane complex amplitude

\[ W(\vec{u}) = A(\vec{u}) e^{i\phi(\vec{u})} \]

Cosine aberration in pupil phase

\[ \phi(\vec{u}) = \frac{2\pi h}{\lambda} \cos \left( 2\pi \vec{f} \vec{u} + \theta \right) \]

EXAMPLE:
Earth-like planet around Sun-like star is ~1e-10 contrast
In visible light, h=1.6e-12 m (0.0012 nm) = 1e-10 speckle

1e-10 speckle (or 1e-10 contrast planet) around Sun at 10pc = 0.1 ph/sec/m²/um
On a 4-m telescope, with 10% efficiency and a 0.5 um spectral band:
Earth = 0.6 ph/sec
To measure phase and amplitude of speckle requires ~10 photon
10 photon = 16 sec
→ This spatial frequency needs to be stable to 1/1000 nm over ~ minute
Focal plane AO and speckle calibration

Use Deformable Mirror (DM) to add speckles

**SENSING**: Put “test speckles” to measure speckles in the image, watch how they interfere

**CORRECTION**: Put “anti speckles” on top of “speckles” to have destructive interference between the two (Electric Field Conjugation, Give’on et al 2007)

**CALIBRATION**: If there is a real planet (and not a speckle) it will not interfere with the test speckles

Fundamental advantage:
Uses science detector for wavefront sensing: “What you see is EXACTLY what needs to be removed / calibrated”
High contrast images obtained in NASA labs
Example: PIAA coronagraph lab results

Monochromatic light (800nm, vacuum) 7.5% wide band (770 – 830 nm, in air)

6 \lambda/D_{sky}

3 runs, contrast values averaged from 2 to 4 \lambda/D between 5.1 \times 10^{-10} to 9.1 \times 10^{-10}
(figure shows 7.3 \times 10^{-10} result)

5.1 \times 10^{-8} contrast from 2 to 4 \lambda/D, 2.1 \times 10^{-8} contrast from 3 to 4 \lambda/D
Contrast performance limited by wavefront instability (test in air)
Speckle Control

Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

From:
- 114 e- RON
- 170 Hz frame rate

To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates
MKIDS camera

Photon-counting, wavelength resolving 140x140 pixel camera

Photon-counting near-IR MKIDs camera for kHz speed speckle control under construction at UCSB

Delivery to SCExAO in late 2017
Coronagraphy testbeds for high contrast (< 1e-8) work need to achieve high stability

High Contrast Imaging Testbed (HCIT) is a vacuum facility at NASA JPL

NASA Ames testing PIAA coronagraph / WFC architectures & MEMs DMs.
Technology: components
Multi-zone PIAACMC focal plane mask

Focal plane mask manufactured at JPL's MDL
Meets performance requirements
(WFIRST PIAACMC Milestone report)
Habitable planet imaging: Scientific opportunities

Space allows access to very high contrast (no atmosphere), but aperture size is limited

Ground-based telescopes can be very large (~30m), but the contrast is limited due to atmosphere
Habitable planets in reflected light: separation, contrast

total stellar luminosity: \( L \) (usually scaled to Sun)
Distance to Sun: \( d \) (in pc)

Physical distance to star scales as \( a = L^{1/2} \)
Angular distance (arcsec) = \( L^{1/2} / d \)
  Example: \( d = 10 \text{pc}, L = 1 \rightarrow 0.1'' \)

Contrast \( \sim 2e-10 \) for Earth at maximum elongation

**Contrast for Earth-like planets in habitable zone = \( 2e-10 / L \)**
  Example: \( L = 0.01 \) (M type star) \( \rightarrow \) contrast = \( 2e-8 \)

Orbital period \( P = \sqrt{a^3/M} \)
  Example: Proxima Centauri...
  1/600 Sun luminosity, 0.123 Sun Mass, \( d = 1.3 \text{ pc} \)
Habitable planets in reflected light: separation, contrast

- Total stellar luminosity: \( L \) (usually scaled to Sun)
- Distance to Sun: \( d \) (in pc)

Physical distance to star scales as \( a = L^{1/2} \)
Angular distance (arcsec) = \( L^{1/2}/d \)
  
  Example: \( d=10\text{pc}, L = 1 \rightarrow 0.1” \)

Contrast \( \sim 2\times10^{-10} \) for Earth at maximum elongation

**Contrast for Earth-like planets in habitable zone = \( 2\times10^{-10}/L \)**
  
  Example: \( L=0.01 \) (M type star) \( \rightarrow \) contrast = \( 2\times10^{-8} \)

Orbital period \( P = \sqrt{a^3/M} \)
  
  Example: Proxima Centauri...
1/600 Sun luminosity, 0.123 Sun Mass, \( d=1.3 \text{ pc} \)
  
  Orbital radius : \( a=0.04 \text{ AU} \)
Angular separation = \( a/d = 0.03 \text{ arcsec} \)
Contrast = \( 1.2\times10^{-7} \)
Orbital Period = 8 day
Proxima Centauri

- Mercury's Orbit
- Proxima b Orbit
- Habitable Zone

- Period: 11.186 days
- Minimum mass: 1.27 Earth masses

- Mass: 0.12 solar masses
- Luminosity: 0.00155 solar luminosities
- Rotation period: 83 days
- Temperature: 2800 Celsius
- Distance to Earth: 4.23 light-years

Sun | Alpha Centauri A | Alpha Centauri B

Rv (km/hour) vs Days since 1 Jan 2016
Habitable Planets: Contrast and Angular separation
Ground-based observation opportunities

1 Re rocky planets in HZ for stars within 30pc (6041 stars)

- M-type stars
  - $\lambda/D = 1600\text{nm}$
  - $D = 8\text{m}$
- K-type stars
  - $\lambda/D = 1600\text{nm}$
  - $D = 8\text{m}$
- G-type stars
  - $\lambda/D = 1600\text{nm}$
  - $D = 30\text{m}$
- F-type stars
  - $\lambda/D = 1600\text{nm}$
  - $D = 30\text{m}$

Around about 50 stars (M type), rocky planets in habitable zone could be imaged and their spectra acquired [assumes 1e-8 contrast limit, 1 $\lambda/D$ IWA]

K-type and nearest G-type stars are more challenging, but could be accessible if raw contrast can be pushed to ~1e-7 (models tell us it's possible)

Thermal emission from habitable planets around nearby A, F, G type stars is detectable with ELTs
Imaging habitable planets from space and ground

---------- Space ----------

Habitable planets can be imaged around nearby Sun-like stars with 2-4+m telescope

---------- Ground ----------

Next generation of 30-m telescopes will image habitable planets around nearby low-mass stars
Backup slides: Coronagraph design
Types of Coronagraphs

3 main approaches to remove starlight:

- Block starlight BEFORE it enters the telescope using a large *external occulter* ~50000 km in front of the telescope

- Design masks and optical components inside the telescope to induce starlight destructive interference at the expected location of a planet in the image: *internal coronagraph* (*this lecture*)

- Induce destructive interference between beams of multiple telescopes: *nulling interferometer*
Internal Coronagraphs: main approaches

**Apodization**

**Beam splitting and destructive interference**

**Phase masks in focal plane**

**Amplitude masks in focal plane**
Lyot Coronagraph

Developed by Bernard Lyot in 1930 to observe the solar corona

It is the origin of many current high performance coronagraph designs

Opaque mask in focal plane

Lyot stop in pupil plane

Final image
Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
Coordinates in focal plane : u,v
* denoting convolution (product = convolution in Fourier transform)
Lyot Coronagraph explained by Fourier transforms

Full set of equations (explained in next slides):

Entrance pupil of telescope: $P_1(x,y)$
Focal plane complex amplitude (before focal plane mask): $F_1(u,v)$

$$F_1(u,v) = \text{FT} \left( P_1(x,y) \right)$$

Focal plane mask complex amplitude transmission: $M(u,v)$
Focal plane complex amplitude (after focal plane mask): $F_2(u,v)$

$$F_2(u,v) = F_1(u,v) \times M(u,v) = \text{FT}(P_1(x,y)) \times M(u,v)$$

Exit pupil plane:

$$P_2(x,y) = \text{FT}^{-1}(F_2(u,v)) = \text{FT}^{-1}(\text{FT}(P_1(x,y)) \times M(u,v)) = P_1(x,y) \ast \text{FT}^{-1}(M(u,v))$$

With * denoting convolution

$$P_3(x,y) = L(x,y) \times P_2(x,y)$$

$$P_3(x,y) = L(x,y) \times (P_1(x,y) \ast \text{FT}^{-1}(M(u,v)))$$

$$F_3(u,v) = \text{FT}(L(x,y)) \ast (F_1(u,v) \times M(u,v))$$

Coronagraphy problem: minimize $P_3(x,y)$ for on-axis point source
Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
Coordinates in focal plane: u,v
* denoting convolution (product = convolution in Fourier transform)
Focal plane image = FT of pupil complex amplitude

Entrance pupil of telescope: $P_1(x,y)$
Focal plane complex amplitude (before focal plane mask): $F_1(u,v)$
$F_1(u,v) = \text{FT}(P_1(x,y))$
Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude $\leftrightarrow$ focal plane complex amplitude

Coordinates in pupil plane: $x,y$
Coordinates in focal plane: $u,v$
* denoting convolution (product = convolution in Fourier transform)
Inserting an opaque mask in the focal plane

Focal plane mask complex amplitude transmission: $M(u,v)$
Focal plane complex amplitude (after focal plane mask): $F_2(u,v)$

$$F_2(u,v) = F_1(u,v) \times M(u,v) = \text{FT}(P_1(x,y)) \times M(u,v)$$
Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
Coordinates in focal plane: u,v
* denoting convolution (product = convolution in Fourier transform)
Lyot Coronagraph: light distribution in output pupil plane

Exit pupil plane:
\[ P_2(x,y) = FT^{-1}( F_2(u,v) ) \]
\[ = FT^{-1} ( FT(P_1(x,y) \times M(u,v) ) ) = P_1(x,y) \ast FT^{-1}(M(u,v)) \]
Lyot Coronagraph explained by Fourier transforms

Pupil plane complex amplitude ↔ focal plane complex amplitude

→ Fourier transform
← Inverse Fourier transform

Coordinates in pupil plane: x,y
Coordinates in focal plane : u,v
* denoting convolution (product = convolution in Fourier transform)
Lyot Coronagraph: Lyot stop (L)

\[ P_3(x,y) = L(x,y) \times P_2(x,y) \]
\[ P_3(x,y) = L(x,y) \times (P_1(x,y) \times FT^{-1}(M(u,v))) \]
\[ F_3(u,v) = FT(L(x,y)) \times (F_1(u,v) \times M(u,v)) \]
Numerical simulation of final image for 10:1 contrast

No coronagraph

With Lyot Coronagraph
A more fancy coronagraph design

Phase Induced Amplitude Apodized Complex Mask Coronagraph (PIAACMC)

Lossess apodization with remapping optics (PIAA)

Conventional apodizer (optional)

Phase-shifting partially transmissive circular focal plane mask

Lyot mask (exact pupil geometry)

Inverse PIAA module

Science focal plane
Lyot Coronagraph: optimizations

Conventional Lyot coronagraph is limited in performance:
- cannot reach extremely high contrast (some light in pupil)
- tradeoff between throughput and contrast
- not able to get high contrast close to the optical axis

Optimization goal: make pupil dark inside Lyot mask

Possible optimizations include:
1. Redesign of focal plane mask
   - Band-limited
   - Use phase as well as (or instead of) amplitude
2. Apodize entrance aperture
Lyot Coronagraph

Phase Mask Coronagraph

4 quadrant coronagraph

Optical vortex coronagraph

Angular groove phase mask coronagraph

8th order

4th order

8 octant coronagraph

Phase knife coronagraph

Optical differentiation coronagraph

Apodized Pupil Lyot Coronagraph

Band limited coronagraph

4th order

8th order
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
Achromatic solutions exist.
Phase-Induced Amplitude Apodization Coronagraph (PIAAC)
Lossless apodization by aspheric optics.

Guyon, Belikov, Pluzhnik, Vanderbei, Traub, Martinache ... 2003-present
"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, 4\textsuperscript{th} order
   VNC
Shao et al., Menesson et al. 2003
Destructive interference between 2 copies of the pupil, sheared by some distance.
4\textsuperscript{th} 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
Visible Nuller Coron. (VNC)

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

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

4th order null

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

A properly placed and shaped occulter can drop a deep shadow of starlight over a telescope while allowing planet light to pass unimpeded.