OLIVIER
(Optical Long-baseline Interferometer for Visible-Infrared Earth Reconnaissance)

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Science motivation, goals and challenges

Science motivation

- Find habitable planets
- Discover extraterrestrial life

Science goals

- Characterize living conditions on the planet
  - Map exoplanets surface
  - Physical characteristics
  - Identify life

Comparable to the Earth

Planets most likely to harbor life

Target: Observing Super Earth or Earth mass planet

$$M_{Earth} < M_{planet} < 10\ M_{Earth}$$

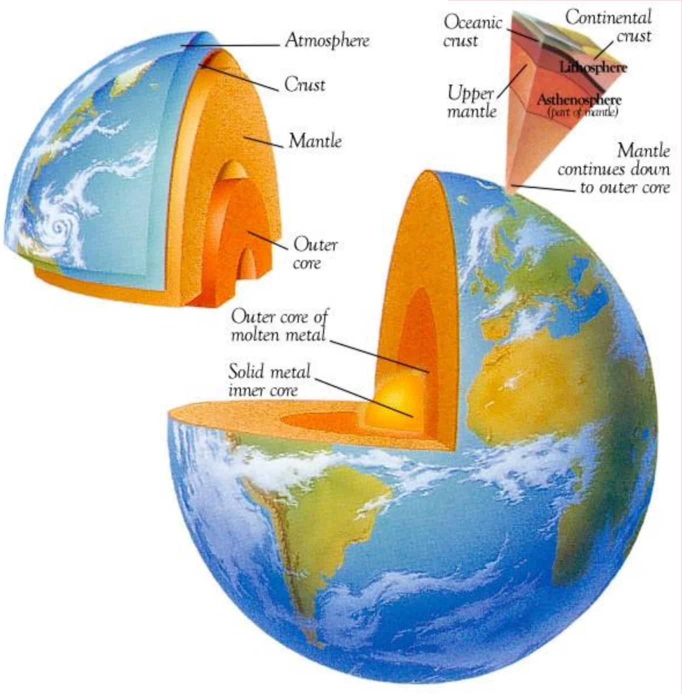
Looking for

- liquid water on its surface

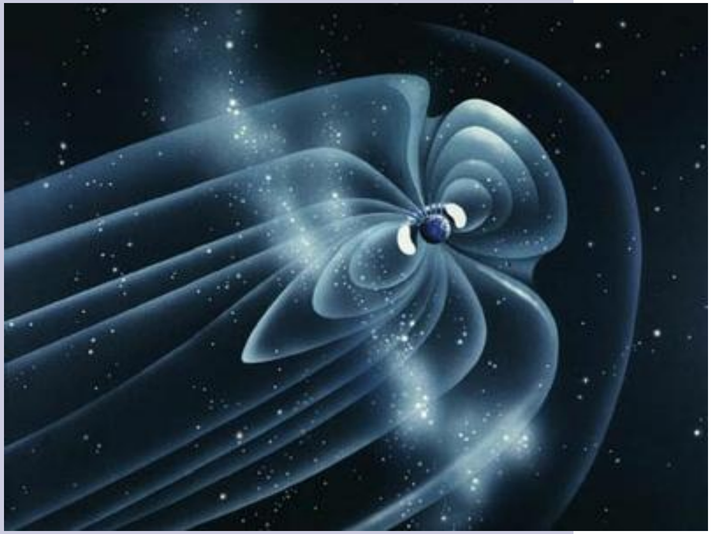
  $T_{surface} > 0$ °C

- Terrestrial planet/ solid surface planet:

  Iron and rock bulk



http://greenearthbd.blogspot.com/2011/01/internal-structure-of-earth.html



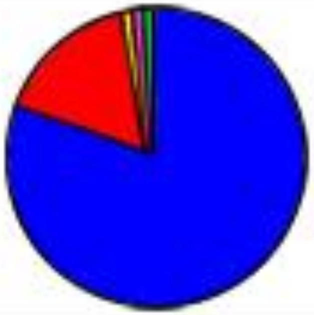
http://nasascience.nasa.gov/heliophysics/focus-areas/magnetosphere-ionosphere/

Comparable to the Earth

- Earth atmospheric composition

Dry Air Expressed in Volumes	
Nitrogen (N_2)	78.1%
Oxygen (O_2)	20.9%
Argon (A)	0.9%
Carbon dioxide (CO_2)	0.035%
Others	0.065%

Others : Neon (Ne)
Helium (He)
Krypton (Kr)
Hydrogen (H_2)
Xenon (Xe)
Ozone (O_3)
Radon (Rn)



Analysis: Planet Reflection of Stellar Radiation

- Observation in the visible, NIR and MIR

- Planet's atmospheric/ surface properties:

- Planet's bulk and atmospheric composition
- Atmosphere and surface temperature
- Presence and nature of clouds
- Behavior of its environment as a function of time

$T_{surface}$ depends on R_{planet} and $d_{star/planet}$ but also highly on mass and composition of its atmosphere

Analysis: Planet Reflection of Stellar Radiation

- **Pressure :** $P_s = g \frac{m_a}{4\,\pi\, R_p^2}$ *Where m_a , mass of the atmosphere, R_p : radius of the planet*
- **Albedo :**

Atmospheric trace gas abundances and distributions, presence of clouds and aerosols.

Stellar energy absorbed by the planet:

$$F_* \,\pi R_p^2 \,(1 - \rho)$$

Where F_* is star irradiance and ρ, albedo.

- **Temperature :**

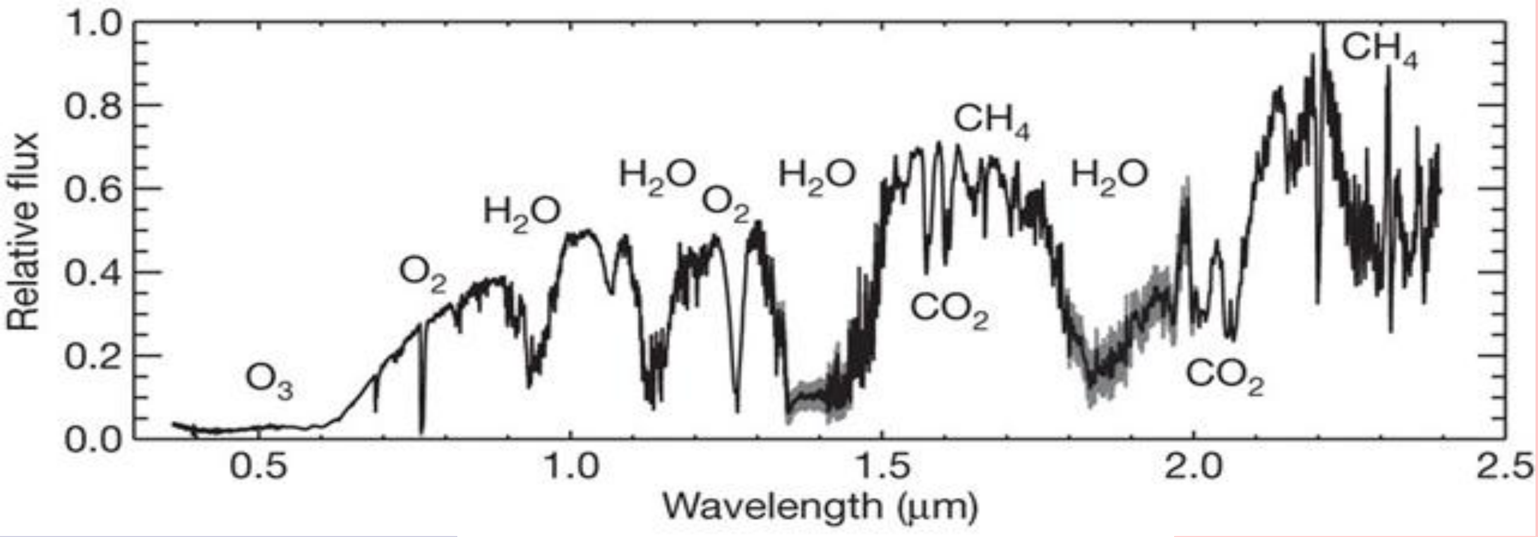
- ***<u>Assumptions :</u>***

- *planet is heated by solar radiation*
- *Planet radiates as a Black Body*

$$\sigma\, T_e^4 = \frac{F_*(1-\rho)}{4}$$

Analysis: Surface/Atmosphere Properties

- Atmosphere composition given by spectral absorption data



Spectrum of Earth atmosphere

- $T_{surface}$: observation in $\Delta\lambda \in [8\ 12]\mu m$ because of small atmospheric absorption of O_2 and H_2O

Analysis: Surface/Atmosphere Properties

- **Surface composition**: visible spectra region gives more information than MIR (except for CO_2 ice detectable in $\Delta\lambda = [10\ 12]\mu m$)

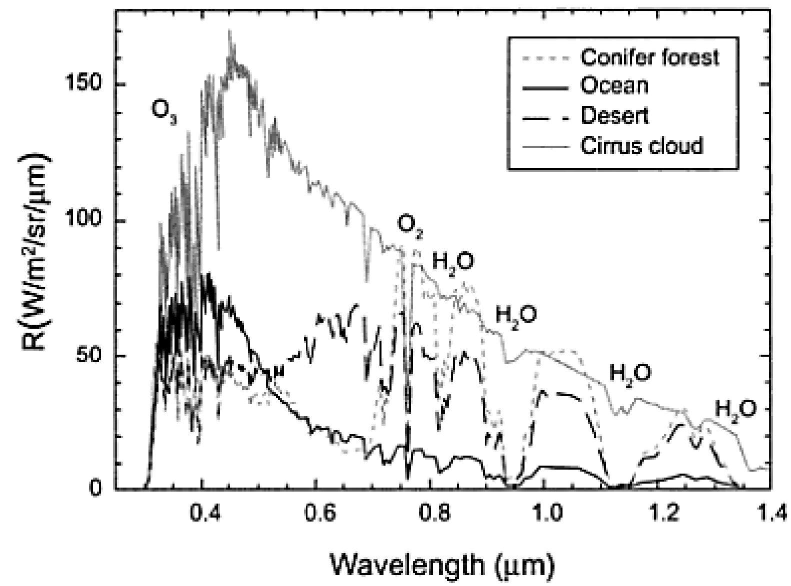


Fig. 7. Surface reflectivity spectra. This diagram shows simulated radiance spectra along lines of sight through Earth's atmosphere over surfaces of different types. In all cases, the incoming spectrum of sunlight was the same, but the radiation reflected back to the observer is quite diverse. This behavior allows us to understand surface composition in remotely sensed data. Image credit: D. Crisp and R. Hasler.

Biosignatures

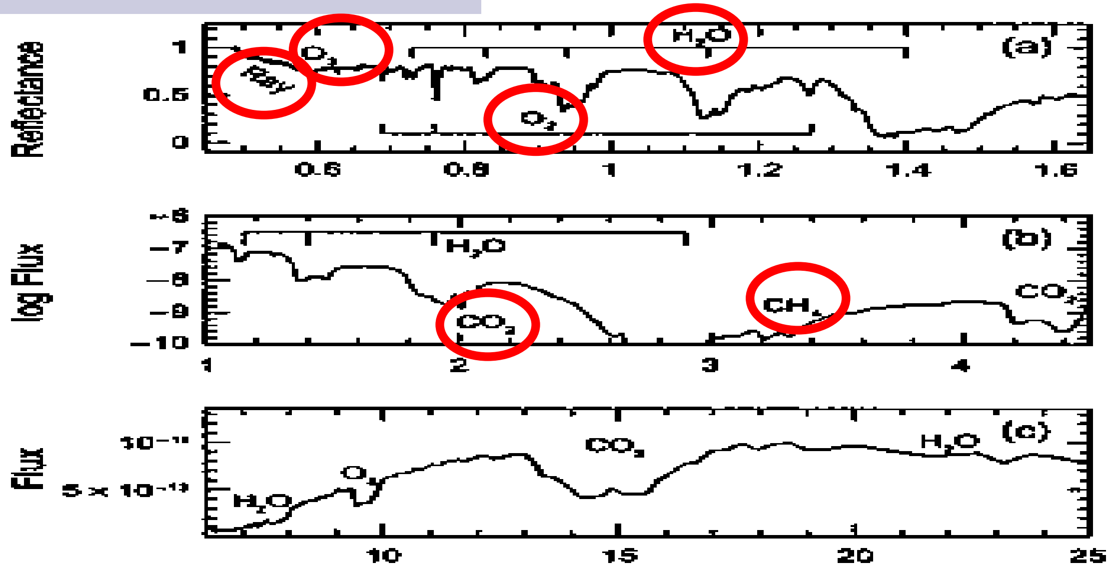


Fig. 8. Earth's observed disk-integrated spectrum. (a) Visible wavelength spectrum from Earthshine measurements plotted as normalized reflectance (*Turnbull et al.*, 2006). (b) Near-infrared spectrum from NASA's EPOXI mission with flux in units of W m^{-2} μm^{-1} (*Robinson et al.*, 2010). (c) Mid-infrared spectrum as observed by Mars Global Surveyor en route to Mars with flux in units of W m^{-2} Hz^{-1} (*Pearl and Christensen*, 1997). Major molecular absorption features are noted, including Rayleigh scattering.

Also N_2O, CH_3Cl …

- Presence of vegetation:

looking for "red edge" effect $R_{\lambda > 0.75 \mu m} \approx [6-20] \times R_{\lambda\, visible}$

Challenges

- Faint light from the planet:
  - 10^{10} fainter than its star in the visible and 10^{7} in the infrared
    - Need to suppress light from host star for a high SNR
    - Good enough angular resolution so that photons can be collected by the planet

- Planet size to have albedo, emissivity and effective temperature

- One observation includes all data properties: difficult to separate them from each other

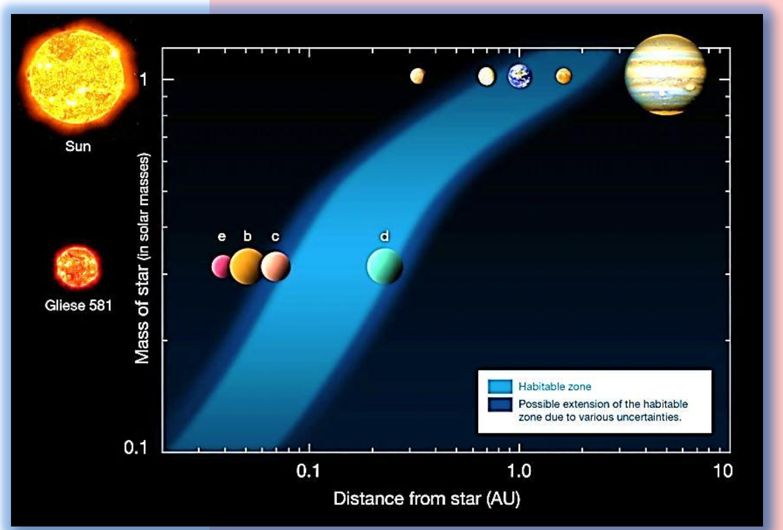
- Easier to detect expanded atmosphere with large scale height

But for terrestrial planet : high bulk density, thin atmosphere of high molecule weight, smaller atmosphere scale heights.

- Detection of 5% variation :
  - detect weather
  - rotational period and seasonal changes in cloud patterns
- Discovery of an unknown atmospheric environment => possible misinterpretation

Beyond Earth like planet

- Planet orbiting a M dwarf star:
  - Less UV radiation => longer lifetime for biosignatures
  - Habitable zone closer to the star



- Extreme life conditions release requirements
  - Look for liquid, but not necessarily water
  - Acid environment
  - Volcanic environment
  - Ice
  - Kilometers under the surface

"Terrestrial Planet Atmosphere and Biosignatures" by Victoria Meadows, Sara Seager.

System Challenges

- Looking at our solar system from 10pc away
  - In the visible
    - Earth is ~1e-10 contrast
    - Zodiacal light would be several 100x brighter than Earth when integrated, and brightest near the star
  - In the near IR (~2um), similar contrasts
  - Earth is brightest planet in the thermal IR ~10um at ~1e-6 contrast
  - At high contrast, stars are not point sources, and inner working angle is affected
  - Habitable zone is ~.1'' (IWA = .1'')

Requirements: Baseline

- Assume 4λ/D resolution across planet

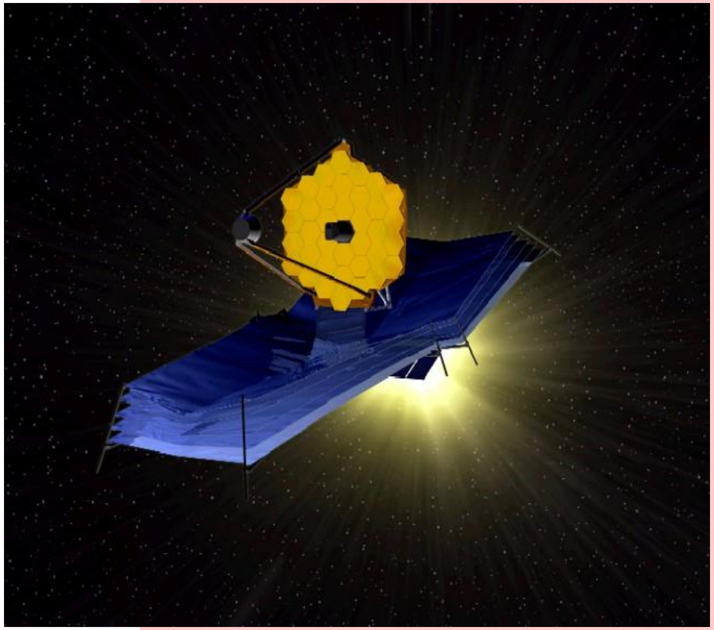
Targets	Baseline (km) (λ=.5μm)	λ=2μm	λ=10μm
Earth (10pc)	12.2	48.82	244.1
1 (known)	1.84	7.37	36.89
10 (known)	8.71	34.85	174.24
50 (known)	19.80	79.18	395.91

Requirements: Telescope

- Telescope diameter should be small enough to not resolve star, but large enough to resolve separation between star and planet

$$D = \frac{\lambda}{\sin(\theta)}$$

- Dmin = 2m (λ=.5μm), 4m (λ=1μm), 40m (λ=10μm)
  - For θ = .05’’ (IWA of coronagraph is 2 λ/D)



Wavelength Tradeoffs

	Visible (0.5µm)	Thermal (10µm)
IWA	0.1’’	0.1’’
Contrast	1e-10	1e-6
Telescope Size	2m	40m
Interferometer Baseline	12.2km	244.1km
Biosignatures	Yes	Sort-of

Requirements: Coronagraph

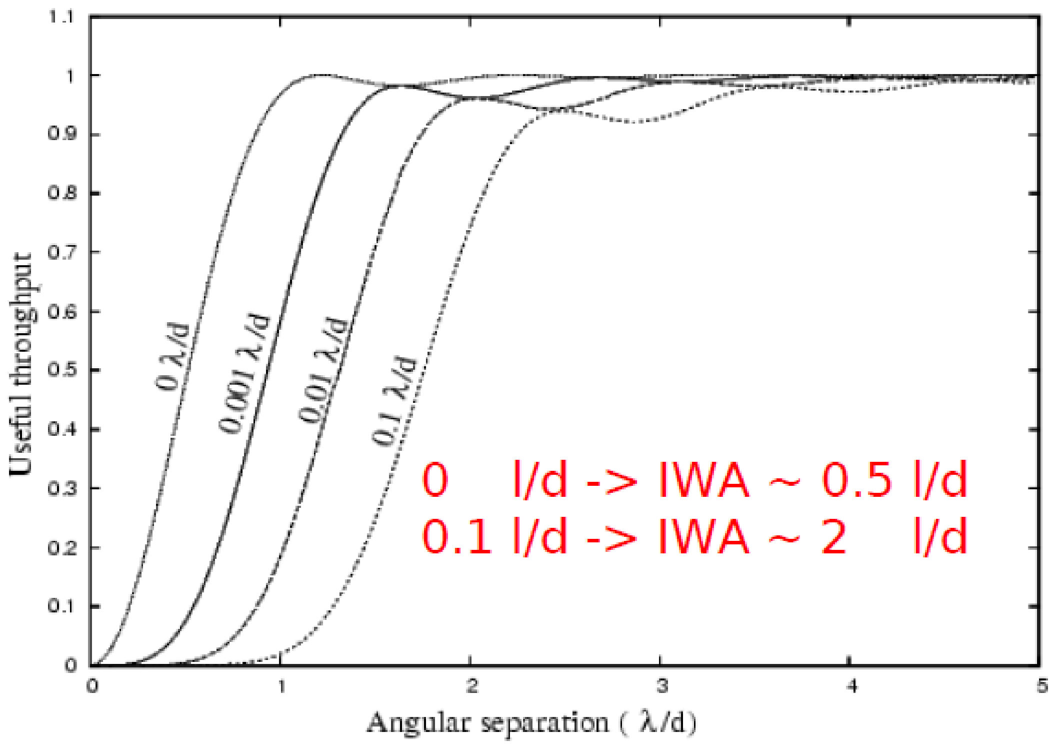
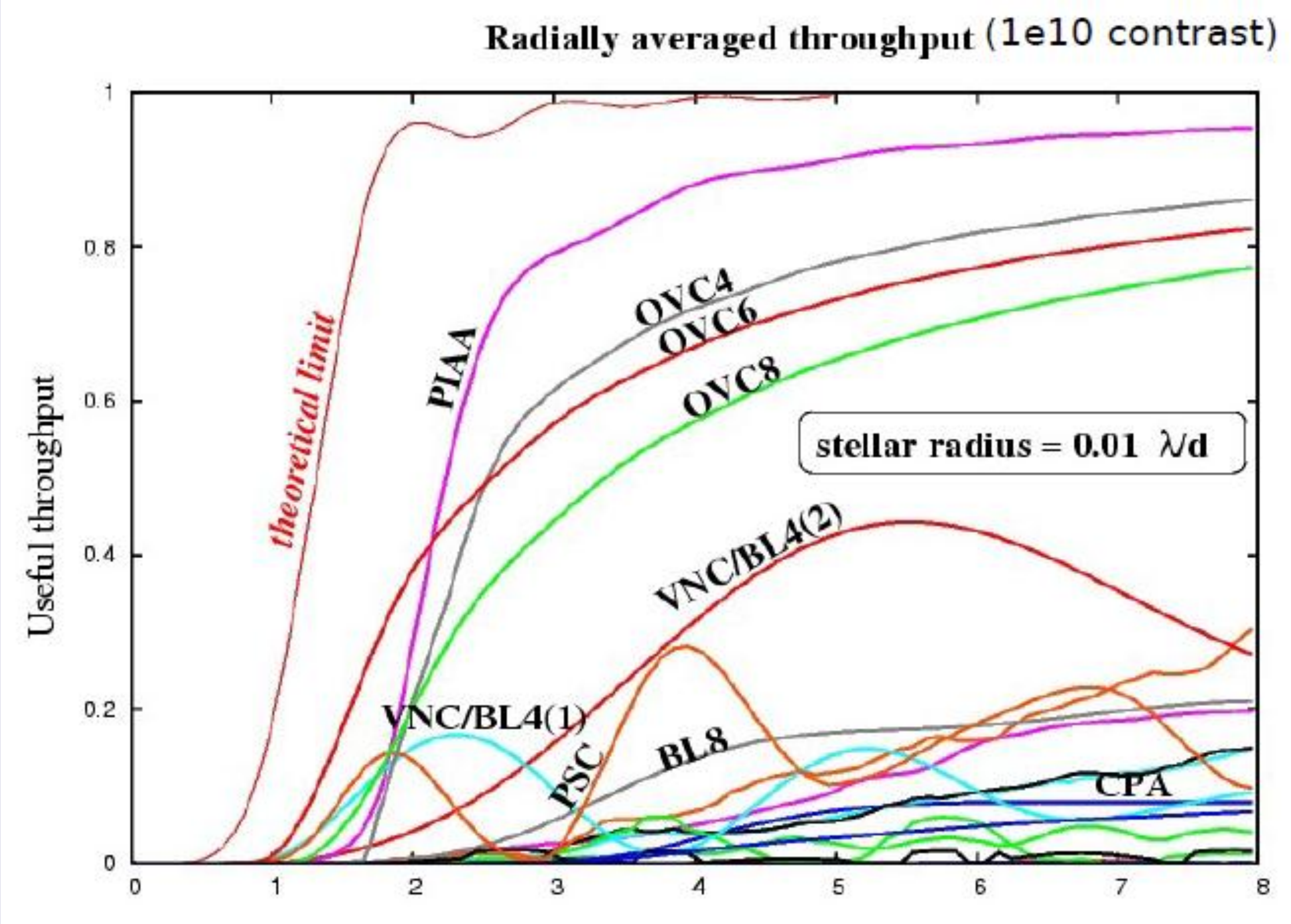


Fig. 5.— Upper limit on the off-axis throughput of a coronagraph for different stellar radii.

- Sun is ~.46mas at 10pc, = .01 λ/D
- Theoretical limit of IWA is ~1.3 λ/D

Coronagraph



PIAA has the best practical limit for dealing with stellar angular size (2λ/D)!

Coronagraph

- Phase Induced Amplitude Apodization (PIAA)
  - Pupil re-mapping using aspheric mirrors, followed by opaque focal plane mask, followed by “reverse” PIAA mirrors to restore image
  - Keeps advantages of classical amplitude apodization
    - Robustness
    - Low sensitivity to stellar angular size
    - Low sensitivity to small pointing errors
  - But also has advantages of nearly full throughput and no loss of angular resolution, mostly achromatic

Extreme AO

- To reduce and calibrate residual and slowly varying wavefront errors (speckle)
- Use starlight blocked by focal plane mask as pointing measurement
- Polarimetric Differential Imaging
  - Planet reflected light is polarized, speckles are not
  - Can only detect reflected light planets (OK for us)

Planet Noise Dominates Star Noise

- Planet flux accounts for over 80% of flux in 93.8% of 250 potential planet detections (previous work) when considering only star+planet flux

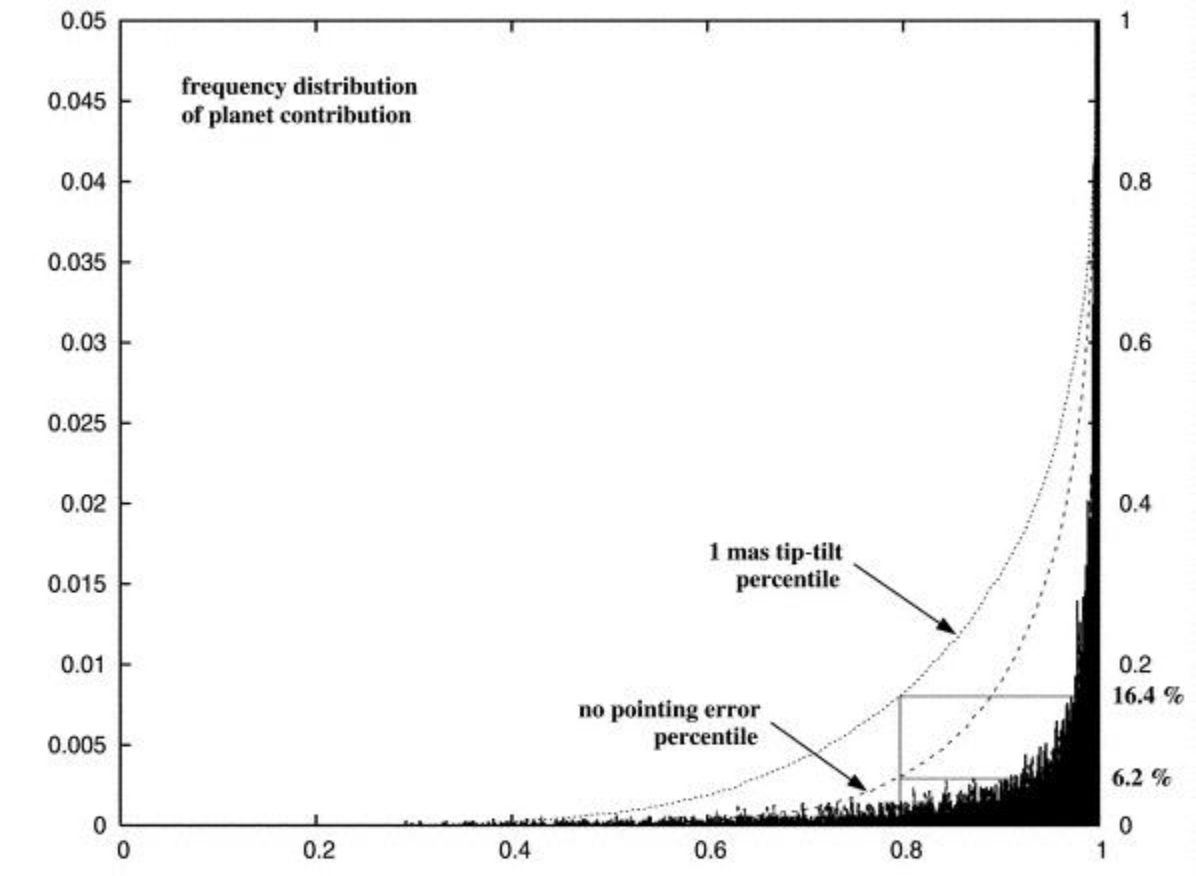


Figure from F. Martinache, O. Guyon, et. al., 2006

(Exo)Zodiacal Light

- Zodiacal and Exozodiacal light will dominate noise calculations
- Exozodiacal light content in other systems is not well known

Exozodi[a]	m_V Contribution from I_z[b]	F_z at 5 pc[c]	F_z at 10 pc	F_z at pc	CPA F_z at 10 pc[d]
0...	31.49 [30.22]	1.03 [1.10]	1.12 [1.39]	1.49 [2.55]	2.09 [4.49]
1...	30.30 [29.03]	1.09 [1.29]	1.36 [2.16]	2.45 [5.65]	4.27 [11.47]
2...	29.74 [28.47]	1.15 [1.48]	1.61 [2.94]	3.42 [8.75]	6.45 [18.44]
5...	28.89 [27.62]	1.33 [2.07]	2.33 [5.26]	6.33 [18.05]	12.99 [39.36]
10...	28.19 [26.92]	1.64 [3.03]	3.54 [9.14]	11.17 [33.54]	23.88 [74.22]
20...	27.46 [26.19]	2.24 [4.97]	5.96 [16.88]	20.85 [64.53]	45.67 [143.95]
50...	26.48 [25.21]	4.06 [10.78]	13.23 [40.1]	49.91 [157.5]	111.04 [353.12]

Table from F. Martinache, O. Guyon, et. al., 2006

Exposure Time for Planet Imaging

- $t_{image} =$
  $$\frac{2n_x\lambda^2}{\pi F_0 \Delta\lambda D^4 T}\left(\frac{S}{N}\right)^2 10^{0.8(M_p+5\log[d]-5)}\left(\left(\frac{206265}{1rad}\right)^2 (10^{-0.4z}+\mu 10^{-0.4x})+\zeta 10^{-0.4m_*}\left(\frac{\pi D^2}{4\lambda^2}\right)\right)/\sqrt{N_{tel}}$$
- Note: calibrated to NWO estimate of observing an Earth-like planet in a Solar System twin at 10pc in 3.3 hours with S/N=10, D=4m

- For our instrument, D=4m, $N_{tel} = 10$
  - $\rightarrow t_{image} = 1.0\ hours$ for an Earth-like analog at 10 pc
  - Can observe 95/101 currently confirmed exoplanets with known distances, semi-major axes, stellar V magnitudes, and planetary radii with <24 hours needed per each source

Formula from A. Roberge et. al. 2009

Exposure Time for Spectroscopy

- $t_{spec} \sim \left(\frac{\Delta\lambda}{\lambda/R}\right) t_{image}$
  - $\Delta\lambda = 88nm, \lambda = 551nm, R = 100$ for the calculation
  - $t_{spec} \sim 16.7hours$ for Earth-like analog
  - 92/101 Exoplanets with known parameters still observable with spectrograph with <24 hours for each source

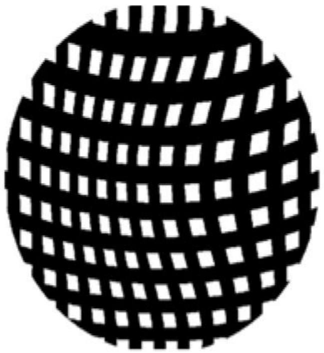
Formula from A. Roberge et. al. 2009

Spectrography

- Low Resolution (R=100), detecting broad features, more photons per bandwidth
- Must work with coronographs
- Must work with beam combiner OR use many Spectrographs
- Must provide ability to resolve multiple image regions
  - Masking, Fiber Pickoffs, etc.
  - Something new?

Spectrography Challenges

- Similar to LBT Project, but Multiple Baselines
- Disperse Each Baseline?
- Disperse Fringe Blob, Reconstruct in Software?
- Use a CGH, with one pattern per baseline, all superimposed?



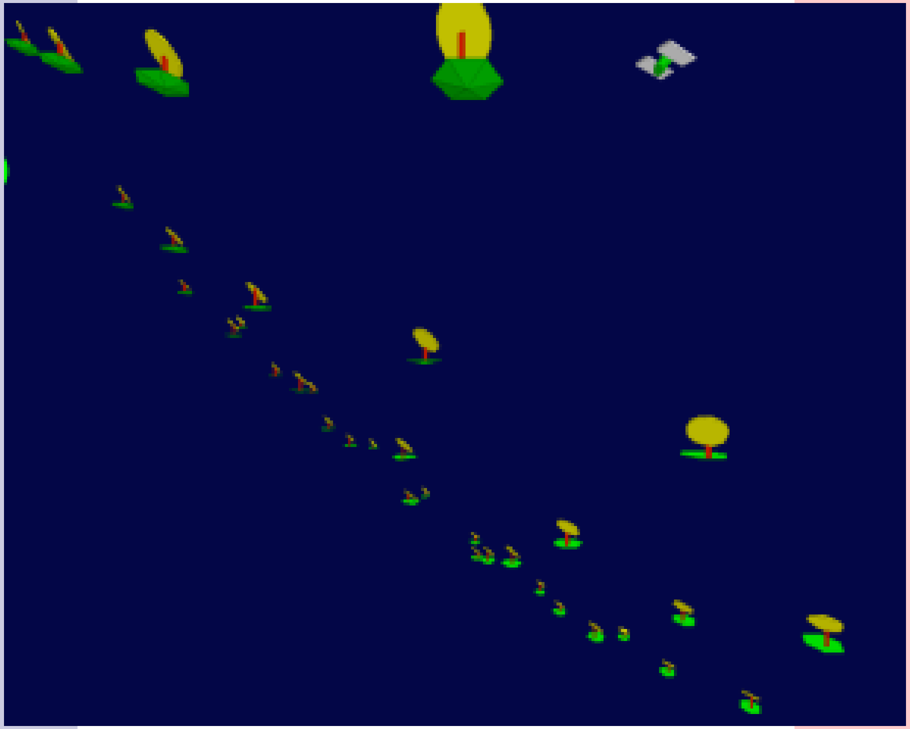
- Chunyu Zhao: Computer Generated Holograms for Optical Testing

Physical Structure

- Large baseline requirements impart difficulties in manner of beam combination
  - Rigid
- Free Formation Flying
  - No rigid structure between telescopes
  - Introduces stringent requirements on OPD between arms and the recombiner

Possible Formation Set-Up

- Utilize a hypertelescope concept
  - Position telescopes in a curved plane with beam recombiner located at the focus



Possible Formation Set-Up

- Paraboloid allows for a compact recombiner at the focus
- Spherical provides simple metrology at the curvature center but will also be spherically aberrated.
- Reduces amount of path-length compensation required in redirecting the array

Arrangement

- Some freedom in choice of formation such as a non redundant case vs. periodic
  - Periodic used for coronography
- Stronger redundancy will improve the dynamic range (fully densified pupil)
  - Greater luminosity gain concentrates most of the light in the central peak

Delay Lines

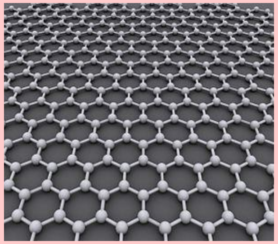
- Not needed
  - Use the vacuum of space rather than introducing any tubes or fibers
- Utilize small mirrors within the recombiner to fine adjust any OPD introduced from the flying formation.
  - Formation flying will get a course OPD on the order of millimeters

Beam Combination

- Considering Visible to NIR still wouldn’t allow for digital recording (100s of THz).
  - Must physically combine beams

Far Future Tech

- Directly Measure Wavefront
  - Combine apertures electronically, not optically
  - Possible in Radio (MHz to GHz)
  - Microwave transmitter electronics good to ~30 GHz
  - ~500 THz Needed for Visible
  - Moore's Law may suggest 5 THz in 50 Years (5 Ghz Today) for commercial parts
  - 100 GHz on graphene today
  - Photodiodes available, several GHz
    - http://www.technologyreview.com/computing/24482/?a=f

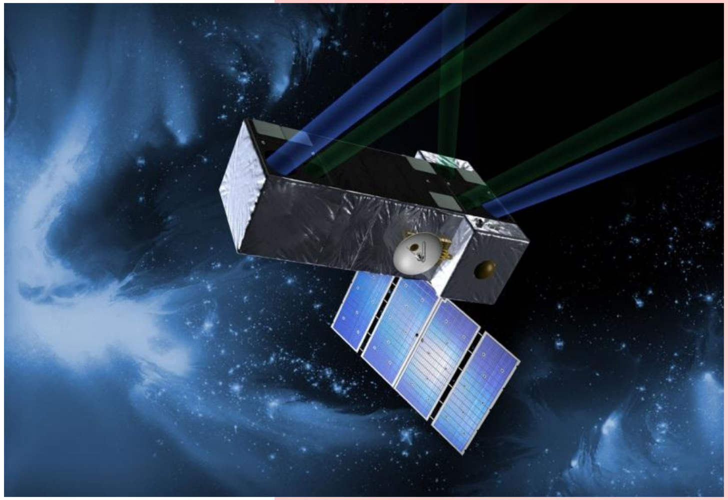


Is This Insane?

- JWST
  - Started in 1996
  - $6 Billion over budget of $2 Billion
  - Started as a visible light telescope...
  - 6.5 meter diameter
- 10x as many scopes as JWST, only marginally smaller, PLUS beam combiner and advanced station keeping hardware
- $70 Billion? More?

Other (Cancelled)Space-Based Interferometry Missions

- Terrestrial Planet Finder (TPF)
  - TPF-I: Infrared, multiple small telescopes, nulling to reduce starlight by 10^6
  - TPF-C: Visible, single mirror, 3-4x larger than TPF-I mirrors, coronagraph to reduce starlight by 10^9
- Space Interferometry Mission (SIM)
  - 0.4 to 0.9μm
  - 6m baseline
  - 2 0.5m mirrors
  - Nulling interferometry



Far Future Tech 2

- Orbital Mirror Fabrication

- Advanced Launch Tech