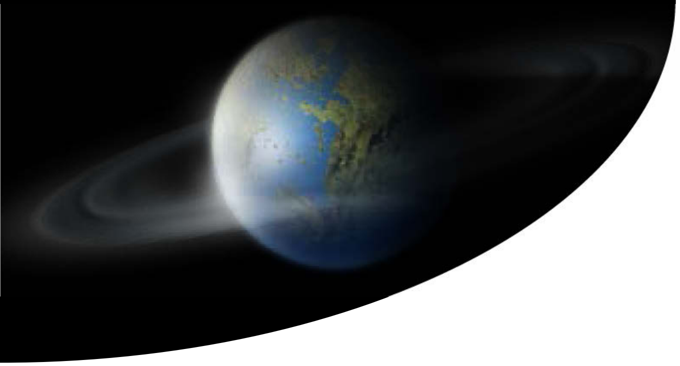

Exoplanet Direct Imaging SAGs

Charley Noecker

Jet Propulsion Laboratory,
California Institute of Technology

Tom Greene

NASA Ames Research Center

ExoPAG 6 – Reno, NV
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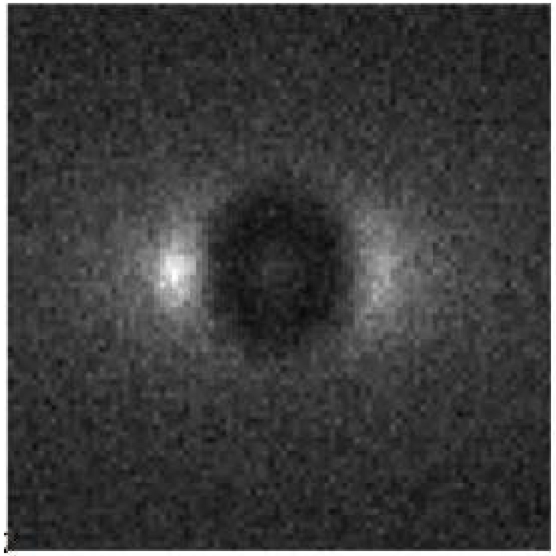

Nearby Earth in 1 zodi disk near 2λ/D (Guyon et al. 2009)

Overview

- SAG 5 is devoted to requirements for a flagship-class direct imaging mission
- A new focus on smaller missions is warranted
  - Diminished expectations for technology and mission funding
  - Exploring a new 2.4m opportunity
- We are planning to form a new SAG to do the same for “moderate” direct imaging mission concepts
  - Probe class ($1B) and 2.4 m options will be prominent
- The proposed SAG 9 for moderate direct imaging will leverage the work done in SAG 5
- Participation in SAG 9 again will be by self-nomination (volunteering)

SAG 5 Membership

- Tom Greene and I are co-chairs. Marie Levine (JPL) is Facilitator.
- ~ 60 scientists, technologists, engineers
- Communicating via http://tech.groups.yahoo.com/group/exopag_flagship/

L name	F name	email	Institution	Interests / Expertise	SAG Task area
Apai	Daniel	apai@as.arizona.edu	UA	Ground-based imaging searches / characterization	
Augereau	Jean-Charles	augereau@obs.ujf-grenoble.fr	IPAG Grenoble	debris disks and exozodiacal dust disks, SPICES concept	dust, planet imaging
Belikov	Rus	ruslan.belikov-1@nasa.gov	NASA ARC	coronagraph technology	
Booth	Jeff	jeffrey.t.booth@jpl.nasa.gov	JPL	Mission architectures	
Breckinridge	Jim	jbreckin@caltech.edu	CIT (adjunct)	Planet imaging telescopes and technologies	
Cahoy	Kerri	kerri.cahoy@gmail.com	MIT / NASA GS	Planetary atmospheres, mission design, DRMs	Science, DRM, mission trades
Cash	Webster	wcash@origins.colorado.edu	Univ Colorado	Science measurements, DRMs, occulters, technology	occulter
Chakrabarti	Supriya	supc@bu.edu	Boston Universi	Technology	
Clampin	Mark	mark.clampin-1@nasa.gov	NASA GSFC	coronagraph science and technology (VNC)	coronagraph
Defrere	Denis	ddefrere@mpifr-bonn.mpg.de	MPIfR Bonn	Imaging exozodiacal disk structures in Hzs and impact on planet imaging	Science
Glassman	Tiffany	Tiffany.Glassman@ngc.com	Northrop Grumn	Starshades / science requirements	occulter
Greene	Tom	tom.greene@nasa.gov	NASA ARC	observations, technology, DRM	editor and co-chair
Guyon	Olivier	guyon@naoj.org	UA / Subaru	coronagraph science and technology (PIAA)	coronagraph
Kaltenegger	Lisa	lkaltene@cfa.harvard.edu	CfA /MPIA	Earth-like atmospheric spectra	Science
Kasdin	Jeremy	jkasdin@Princeton.EDU	Princeton	coronagraphs, occulters, system engineering	occulter and coronagraph
Krist	John	john.krist@jpl.nasa.gov	JPL	coronagraph design & modelling, debris disk imaging	Modeling requirements, post-observation reduction
Levine	Marie	marie.b.levine-west@jpl.nasa.gov	JPL	Technology, observatory system design, requirements & analysis	system engineering
Lilly	Chuck	chuck.lillie@ngc.com	Northrop Grumn	Architecture issues, technology	Occulter & coronagraph
Lisman	Doug	p.d.lisman@jpl.nasa.gov	JPL	coronagraphs, occulters, system engineering	occulter and coronagraph
Lisse	Carey	Carey.Lisse@jhuapl.edu	JHU APL	exosystem spectroscopy / materials characterization	Science
Lo	Amy S	Amy.Lo@ngc.com	NGAS	Science measurements, DRMs, occulters, performance modeling, technology, ground testing	occulter
Lyon	Rick	richard.g.lyon@nasa.gov	GSFC	Flow of requirements into architectures	requirements to architectures
Mandell	Avi	Avi.Mandell@nasa.gov	NASA GSFC	IR spectral characterization of exoplanets	Science
Marley	Joe	joseph.h.catanzarite@jpl.nasa.gov	JPL	Science measurements, astrometry	Science
Marley	Mark	mark.s.marley@nasa.gov	NASA ARC	Planetary atmospheres and giant planet spectra	Science
McElwain	Michael	michael.w.mcelwain@nasa.gov	NASA GSFC	coronagraphy, wavefront control, and IFU spectroscopy and science policy	Science and technology
Noecker	Charley	mcnoecke@ball.com	Ball ATC	Science measurements, DRMs, coronagraphs, occulters, control systems, performance modeling, technology, ground testing	editor and co-chair, occulter and coronagraph, system engineering
Petit	Pascal	petit@ast.obs-mip.fr	Observatoire Mi	stellar magnetic activity via spectroscopy and spectropolarimetry	Science
Pitman	Joe	joe.pitman@exsci.org	ExSci	space telescopes, SE, modeling & simulation, I&T, verification	Strawman concepts and requirements
Postman	Marc	postman@stsci.edu	STScI	Large UV/O mission synergy	Large UV/O mission synergy
Redding	Dave	david.c.redding@jpl.nasa.gov	JPL	integrated modeling	system engineering
Roberge	Aki	aki.roberge-1@nasa.gov	NASA GSFC	Exozodi	Exozodi SAG lead
Serabyn	Gene	eserabyn@jpl.nasa.gov	JPL	Science, coronagraphs, interferometers	ultimate contrast, wavelengths, IWA
Shaklan	Stuart	stuart.b.shaklan@jpl.nasa.gov	JPL	architecture issues	occulter and coronagraph
Shao	Mike	michael.shao@jpl.nasa.gov	JPL	Planet / dust / speckle discrimination, astrometry, coronagraph (VNC)	Science and coronagraph
Smith	Erin C.	erin.c.smith@nasa.gov	NASA ARC	(Occulters)	occulter
Solmaz	Arif	arif.solmaz@gmail.com	Turkey (student)	Transits, exoplanets	
Soummer	Rémi	soummer@stsci.edu	STScI	Science measurements, coronagraphs, occulters	occulter and coronagraph
Sparks	Bill	sparks@stsci.edu	STScI	Biosignatures, circ. Polarization	Science, instrument concepts
Stapelfeldt	Karl	krs@exoplanet.jpl.nasa.gov	JPL	Science performance modeling, targets, dust	Science
Tanner	Angelle	angelle.tanner@gmail.com	Georgia State	target selection, astrometry, high contrast imaging	Science / targets
Tenerelli	Domenick	domenick.tenerelli@lmco.com	LMMSC	coronagraph and occulter missions and technologies	occulter and coronagraph
Trauger	John	John.Trauger@jpl.nasa.gov	JPL	coronagraph and wavefront control technologies	Mission design and performance simulations
Tsvetanov	Zlatan	zlatan@pha.jhu.edu	JHU	observations, science requirements, figures of merit	Science
Turnbull	Maggie	turnbull.maggie@gmail.com	Global Science	Target star characteristics, background objects	Science
Vanderbei	Robert	rvdb@Princeton.EDU	Princeton	Coronagraphs and Occulters	
Vosteen	Amir	amir.vosteen@tno.nl	TNO	nulling interferometry, systems engineering.	
Williams	Darren	dmw145@psu.edu	PSU	Earth-like moons of giant exoplanets	Science

Task Description

- Coronagraph and Occulter SAGs were combined into SAG 5 after ExoPAG 3 (Jan 2011)
- Develop strawman science requirements for direct imaging
  - Groundwork for Astro2010 mid-decade technology downselect
  - Structured to support making comparisons and decisions

1. Start on a 2020+ "flagship" imaging mission

   Flagship ≡ very likely to find & characterize at least one Earth-like planet in the habitable zone of its star

2. Then consider smaller mission(s) along that path

- Meetings with COPAG → initiated effort to define a shared space telescope for exoplanets and UV-opt astrophysics
  - COPAG's flagship definition is consistent with ours

SAG 5 Progress 2011-12

- Established a framework of Science Goals, Objectives, and Musts & Discriminators
  - See description on next page
  - Discussed via email, telecons, and at ExoPAG meetings
- Flagship class mission, COPAG partnership
  → Emphasized terrestrial planets
  - Super-earths, giant planets, and debris disks are included in key Discriminators
- We have essentially finished this work with some caveats:
  - We will not assign scoring at this time
  - Several requirement values are TBR, pending better knowledge
    - Prevalence of Earth-like exoplanets ($\eta_\oplus$) from Kepler
    - Exozodi statistics (brightness and profile) from LBTI or elsewhere
- On track for delivering a report at ExoPAG 7 (Jan 2013)
- Move on to smaller missions (proposed SAG 9)

Unusual Framework for Requirements

- We have articulated

3 overarching science goals → 11 more specific science objectives → Musts (minimum capability) / Discriminators (valuable additions)

- **Musts** correspond to traditional minimum science requirements, but can include technical or programmatic constraints
- **Discriminators** are a new way to handle Baseline and Goal/Stretch requirements
  - Phrased to be independent of mission architecture
- Allows fair comparison of different mission concepts with very different strengths and weaknesses
- Worked with SAG 4 (exoplanet characterization) and SAG 1 (exozodi requirements)
- COPAG has agreed to formulate their requirements in this framework
  ➔ Selection of one mission concept based on the union of both sets of criteria

Science Goals (Top Level)

- Goal1: **Determine the overall architectures** of a sample of nearby planetary systems. This includes determining the numbers, brightnesses, locations, and orbits of terrestrial to giant planets and characterizing exozodiacal dust structures in regions from habitable zones to ice lines and beyond. This information will also provide clues to the formation and evolution of these planetary systems.
- Goal 2: **Determine or constrain the atmospheric compositions** of discovered planets, from giants down to terrestrial planets. Assess habitability of some terrestrial planets, including searching for spectral signatures of molecules and chemical disequilibrium consistent with the presence of life. Determining or constraining surface compositions of terrestrial planets is desirable but is not strictly required.
- Goal 3: Determining or constraining **planetary radii and masses are stretch goals** of this mission. These are not strictly required. However, measuring radii and masses would provide a better understanding of detected planets, significantly increasing the scientific impact of this mission.

Vector from SAG 5 to proposed SAG 9

- How would we modify those goals for a smaller mission?
- Let's look at some examples…

Science Goals A. Minor relaxation

- Goal1: **Determine the overall architectures** of a sample of nearby planetary systems. This includes determining the numbers, brightnesses, locations, and orbits of ~~terrestrial to giant~~ planets and characterizing exozodiacal dust structures in regions from habitable zones to ice lines and beyond. This information will also provide clues to the formation and evolution of these planetary systems.
- Goal 2: **Determine or constrain the atmospheric compositions** of discovered planets, ~~from giants down to terrestrial planets. Assess habitability of some terrestrial planets, including searching for spectral signatures of molecules and chemical disequilibrium consistent with the presence of life.~~ Determining or constraining surface compositions of terrestrial planets is desirable but is not strictly required.
- Goal 3: Determining or constraining **planetary radii and masses are stretch goals** of this mission. These are not strictly required. However, measuring radii and masses would provide a better understanding of detected planets, significantly increasing the scientific impact of this mission.

Science Goals

B. Leave unchanged

- Goal1: **Determine the overall archite**
planetary systems. This includes dete
brightnesses, locations, and orbits of t
characterizing exozodiacal dust struct
zones to ice lines and beyond. This in
clues to the formation and evolution o
- Goal 2: **Determine or constrain the a**
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spectral signatures of molecules and c
consistent with the presence of life. Determining or constraining surface compositions of terrestrial planets is desirable but is not strictly required.
- Goal 3: Determining or constraining **planetary radii and masses are stretch goals** of this mission. These are not strictly required. However, measuring radii and masses would provide a better understanding of detected planets, significantly increasing the scientific impact of this mission.

Several of these goals are likely too difficult for small missions, but there's no need to constrain ambition at the beginning

Science Objectives (condensed)

1. Detect terrestrial planets
2. Measure orbital parameters
3. Obtain multi-band photometry
4. Confirm planets and distinguish among them (motions & colors)
5. Determine or constrain planet masses if possible
6. Spectroscopic characterization of terrestrial planets
7. Detect giant planets
8. Spectroscopic characterization of giant planets
9. Measure location and extent of dust disks
10. Detect and measure substructures in dusty disks to infer planets
11. Understand the evolution of circumstellar disks: pre-planetary to debris

Detailed language

Science Objectives

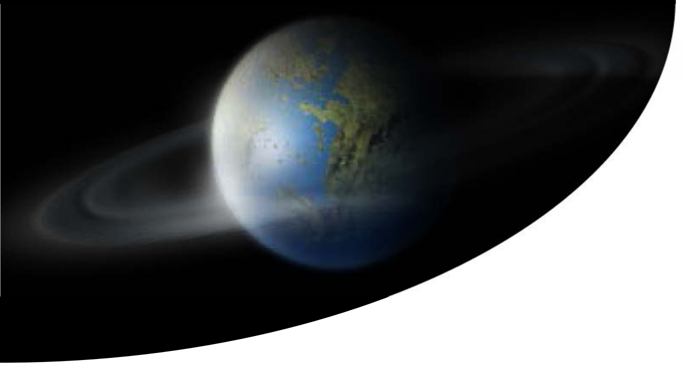
A. Minor relaxation

1. Detect ~~terrestrial~~ planets
2. Measure orbital parameters
3. Obtain multi-band photometry
4. Confirm planets and distinguish among them (motions & colors)
5. Determine or constrain planet masses if possible
6. Spectroscopic characterization of ~~terrestrial~~ planets
7. ~~Detect giant planets~~ Redundant
8. ~~Spectroscopic characterization of giant planets~~
9. Measure location and extent of dust disks
10. Detect and measure substructures in dusty disks to infer planets
11. Understand the evolution of circumstellar disks: pre-planetary to debris

[Detailed language]

Musts and Discriminators

- SAG 5's are too detailed to cover here
- Summarized vaguely in backup slides
- Described in detail in draft report (available on request)
- Musts and Discriminators are where we'll make the most extensive changes between SAG 5 and SAG 9



We welcome your comments

Please join us

Science Objectives (full text, 1/4)

1. Directly detect terrestrial planets that exist within the habitable zones around nearby stars or, alternatively, observe a large enough sample of nearby systems to show with high confidence that terrestrial planets are not present.
2. Measure or constrain orbital parameters (semi-major axis and eccentricity) for as many discovered planets as possible, especially those that show evidence of habitability.
3. Obtain absolute photometry in at least three broad spectral bands for the majority of detected planets. This information can eventually be used, in conjunction with orbital distance and planet radius, to constrain planetary albedos.

Return

Science Objectives (full text, 2/4)

4. Distinguish among different types of planets, and between planets and other objects, through relative motion and broadband measurements of planet color.
5. Determining or constraining planetary masses is highly desired but not required. Determining masses would allow estimates of planetary radii to be made, thereby enabling calculation of planetary albedos (Objective 3).
6. Characterize at least some detected terrestrial planets spectroscopically, searching for absorption caused by O_2, O_3, H_2O, and possibly CO_2 and CH_4. Distinguish between Jupiter-like and H_2O-dominated atmospheres of any super-Earth planets. Such information may provide evidence of habitability and even of life itself. Search for Rayleigh scattering to constrain surface pressure.

Return

Science Objectives (full text, 3/4)

7. Directly detect giant planets of Neptune's size or larger and having Jupiter’s albedo in systems searched for terrestrial planets. Giants should be detectable within the habitable zone and out to a radius of at least 3 times the outer habitable zone radius .
8. Characterize some detected giant planets spectroscopically, searching for the absorption features of CH_4 and H_2O. Distinguish between ice and gas giants, as well as between Jupiter-like and H_2O-dominated atmospheres of any mini-Neptune planets.
9. Measure the location, density, and extent of dust particles around nearby stars in order to identify planetesimal belts and understand delivery of volatiles to inner solar systems.

Return

Science Objectives (full text, 4/4)

10. In dusty systems, detect and measure substructures within dusty debris that can be used to infer the presence of unseen planets.
11. Understand the time evolution of circumstellar disk properties around a wider star sample at greater distances, from early protoplanetary stages through mature main sequence debris disks.

- The Science Goals and Objectives are related as follows

Science Goals	Science Objectives										
	1	2	3	4	5	6	7	8	9	10	11
1. Architectures	✓	✓		✓	✓		✓		✓	✓	✓
2. Compositions			✓	✓	(✓)	✓		✓			
3. Masses & radii			✓	✓	✓					✓	

Return

Musts mapped to Objectives

Musts	Science Objectives										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
M1: detect Earth twin	✓										
M2: detect Jupiter twin							✓				
M3: 14 CumHZs	✓						✓				
M4: 3 CumIHZs	✓						✓				
M5: colors			✓	✓				✓			
M6: fine spectra						✓		✓			
M7: orbital SMA	✓	✓		✓							
M8: oxygen						✓					
M9: water						✓		✓			
M10: all on 1 planet	✓	✓	✓	✓		✓					
M11: absol photometry			✓								
M12: guide on faint star									✓	✓	✓
M13: surface brightness									✓	✓	✓

Return

Discriminators mapped to Objectives

Discriminators	Science Objectives										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
D1: # CumHZs	✓						✓				
D2: # CumIHZs	✓						✓				
D3: max δ-mag	✓						✓				
D4: # confirmed	✓						✓				
D5: # planets, 4 color			✓	✓				✓			
D6: # planets, full spectra						✓		✓			
D7: # planets, part spectra						✓		✓			
D8: NIR and NUV						✓		✓			
D9: common PM	✓						✓				
D10: # orbit SMA	✓	✓		✓							
D11: # astrometric mass				✓	✓						
D12: # absol photometry			✓	✓							
D13: # giants w/ TXPs							✓	✓			✓
D14: # KuiperB w/ TXPs									✓	✓	✓

Return