Study Analysis Group 15
Exoplanet Exploration Program Analysis Group

Science Questions for Direct Imaging Missions

DRAFT

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Table of Contents

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Introduction

This report presents organized input from the international exoplanet community on science questions that can be answered by direct imaging missions.

For each science question we also explore the types and quality of datasets that are either required to answer the question or greatly enhance the quality of the answer. We also highlight questions that require or benefit from complementary (non-direct imaging) observations.

In preparing the report no specific mission architecture or requirements were assumed or advocated for; however, where obvious connections to planned or possible future mission existed there were identified. The report does not include discussion of biosignatures or planets transformed by life; but it does include discussion of the characterization of habitable zone earth-sized planets.

Overview of science questions

Science Questions on Exoplanetary System Architectures & Population	Importance
A1. What is the diversity of planetary architectures? Are there typical classes/ types of planetary architectures? How Common are Planetary Architectures resembling the Solar System?	
A2. What are the distributions and properties of planetesimal belts and eco-zodiacal disks in exoplanetary systems and what can these tell about the formation and dynamical evolution of the planetary systems?	
Science Questions on Exoplanet Properties	**Importance**
B1. How do rotation periods and obliquity vary with orbital elements and planet mass/type?	
B2. Which rocky planets have liquid water on their surfaces?	
B3. What are the origins and composition of clouds and hazes in ice/gas giants and how do these vary with system parameters?	
B4. Which planets have large continents and oceans?	
B5. How do photochemistry, transport chemistry, surface chemistry, and mantle outgassing effect the composition and chemical processes in terrestrial planet atmospheres (both habitable and non-habitable)?	
Science Questions of Evolution and Processes that Change Exoplanets	**Importance**
C1. What processes/properties set the modes of atmospheric circulation and heat transport in exoplanets and how do these vary with system parameters?	
C2. What are the Key Evolutionary Pathways for Rocky Planets?	
C3. What types/which planets have active geological activity, interior processes, and /or continent-forming/resurfacing processes?	

Discussion of Science Questions

The following sections provide a preliminary discussion of possible science questions for direct imaging missions. The questions are organized in three categories: Questions in Category A focus on the statistical assessment of the properties of exoplanetary systems. Questions in Category B focus on the understanding of specific exoplanets. Questions in Category C focus on understanding the details and importance of key processes by establishing causal relations between present-day properties and processes.

A1. What is the diversity of planetary architectures? Are there typical classes/types of planetary architectures? How common are Solar System-like planetary architectures?

Contributors: Daniel Apai

The term “planetary system architecture” is used here as a descriptor of the high-level structure of a planetary system as given by the stellar mass, the orbits and mass/nature of the planets, and the locations/mass of its planetesimal belts.

Understanding the diversity of planetary architectures is important for the following three reasons:

1) The diversity of planetary system architectures is expected to reflect the range of possible pathways of planetary system formation and evolution.
2) To understand how common are true Earth analogs we must understand how common are planetary systems with architectures similar to that of the Solar System.

Our current picture of planetary system architectures builds on five sources: 1) Solar System; 2) Data from transiting exoplanets, primarily Kepler, which probes the inner planetary systems (typically up to periods of approximately 1 year); 3) radial velocity surveys, which provide data on planets with masses typically larger than those accessible to Kepler observations, but some of which cover multi-year periods; 4) microlensing surveys, which are also sensitive to small rocky planets at intermediate periods, but provide a yet limited statistics; 5) direct imaging surveys: capable of probing giant exoplanets at semi-major axes of 8 au or longer.

Based on the extrapolation of the close-in exoplanet population detected by Kepler we do not yet have an efficient method to detect the majority of exoplanets (at intermediate to large periods, with masses comparable to Earth). ESA’a *Gaia* mission is expected to increase the census of known intermediate- to long-period giant planets by about ~3,000 new discoveries. In addition, the proper motion information for the Solar neighborhood will improve the identification and age-dating of co-moving stellar groups which, in turn, will greatly reduce the uncertainties in the giant planet mass—luminosity conversion used by ground-based direct exoplanet imaging surveys, improving the long-period giant planet occurrence rate estimates.

Furthermore, the gradually extending baselines and improving accuracy of radial velocity measurements will also further improve the occurrence rates for short and intermediate-orbit planets (most significantly for neptune-mass and larger planets).

In spite of these significant improvements the occurrence rates of the sub-neptune planets (including rocky and icy planets) at intermediate- to long-period orbits will remain largely unconstrained.

A direct imaging mission would be powerful in surveying low-mass planets at intermediate and long orbits (~1 to 30 au), establishing their orbits or constraining their orbital parameters, and measuring or deducing their masses and sizes.

<u>Sub-questions:</u>

A) *What is the diversity of planetary architectures?* The statistical assessment of the occurrence rate and mass distribution of planets as a function of system parameters (e.g., stellar mass, composition) can constrain and/or verify planet formation models. The dispersion in different parameters (from selection effects-corrected data) can be used to quantify the diversity of the architectures.

B) Are there typical classes/types of planetary architectures? If there are different typical planet formation or evolution pathways, these may lead to the emergence of different classes of planetary architectures (e.g., planetary systems with hot jupiters). The presence of classes of planetary systems may be identified as clustering in the multi-dimensional space that describes planetary architectures.

C) How common are Solar System-like planetary architectures? The local density of the systems in the multi-dimensional parameter space describing planetary architectures at the location of the Solar System provides a measure of the occurrence rate of Solar System-like architectures. Furthermore, in this multi-dimensional parameter space distance-type metrics can be defined to reflect the similarity of planetary system architectures. Although non-unique, such metrics may be used to explore the frequency of systems as a function of distance from the Solar System to establish which nearby systems are the most similar to ours.

Imaging Data Required: *Optical or infrared imaging to identify the presence and location of planets in each system. Multi-epoch imaging (or complementary radial velocity or astrometry) is required to constrain orbital parameters.*

Complementary Non-Imaging Data:

1) *Radial velocity:* Constraints from radial velocity measurements can greatly reduce the number of direct imaging epochs required to establish the orbital elements of the planets. These measurements can also constrain or determine the mass of the target planets.
2) *Microlensing:* Statistical constraints from the WFIRST-Microlensing survey will provide important context for the frequency of medium-separation low-mass planets.
3) *Ground-based adaptive optics imaging:* These observations may be capable of discovering giant exoplanets and providing positions at additional epochs.
4) *Gaia Astrometry:* This dataset will provide orbital elements and masses for a large number of intermediate- to long-period gas giant planets, an important statistical context for the planets to be discovered by the direct imaging mission. Furthermore, for individual targets where the direct imaging mission and Gaia can both detect planets, an improved age estimate can be made for the system using giant planet evolutionary models.

A1 Questions to SAG15:

1) How many epochs are required to establish orbital parameters?
2) To what accuracy should the orbital parameters be measured to?
3) What sample size (number of systems imaged) would be a) minimum required, or be b) optimally suited for answering this question?
4) What statistical constraints will WFIRST-ML, Gaia, and future RV surveys provide?

A1 - Additional Comments:

SDG: There will be an upcoming white paper by Debra Fischer and colleagues on high- precision RV measurements that will be very relevant for this question.
SDG: Rather than identifying a complete understanding of planetary architectures (which may be impossible to achieve), we may want to identify specific hypotheses that should be tested. For example, a hypothesis on the transition between rocky planets and gas giants could have specific, testable predictions.
SDG: We should also consider that, given also complementary measurements, which dimensions of the description of planetary architectures are important and which are not probed sufficiently by existing/future measurements, i.e., prioritize dimensions that are important and unexplored.
SK: We should consider dynamical constraints, such as mean-motion resonances, on the N-dim parameter space, as the dynamical information can be important for understanding the systems.
SK: A related question: are compact planetary systems extremely common? There are some biases and intriguing trends in the existing transit-based data that could be verified with direct imaging.
Needs more discussion:
The Solar System may in many ways differ from typical planetary systems. Which parameters are relevant for this question?
SK? : Jupiter analogs are becoming detectable and this question (at least frequency of Sun-Jupiter pairs) will be answered relatively soon.
DA: There are many parameters that could be used to determine the similarity of a given planetary system and the Solar System; not clear which are more important than others for our purposes and how to weight them.
Consensus: We will need to better define this question.
Very important constraints will be placed on this question by Kepler, K2, RV surveys, GAIA, ALMA,LBTI, and WFIRST-Microlensing. However, each of these will be sensitive to only certain types of planets in certain systems, i.e., not clear that the science question above can be fully addressed by combining heterogeneous constraints from different missions.

A2. What are the distributions and properties of planetesimal belts and eco-zodiacal disks in exoplanetary systems and what can these tell about the formation and dynamical evolution of the planetary systems?

Contributors: Daniel Apai

Direct imaging missions will provide spatially resolved images of exo-zodiacal disks, possibly composed of narrow and/or extended dust belts. In these belts dust is produced by minor body collisions and the dust belts are dynamically sculpted by the gravitational influence of star and the planets, grain-grain collisions, as well as radiation pressure (for reviews see, e.g., Wyatt 2008).

The distribution and properties of exo-zodiacal dust belts (or debris disks) are important as they provide information on:

1) The presence, orbits, and masses of embedded, yet unseen planets.
2) The orbits and masses of planets seen in the direct images, but for which orbits are not known.
3) The inclination of the disk/planet system.
4) Formation and evolution history of the system, including migration and orbital rearrangements of the planets.
5) Compositional constraints on the availability of volatiles/organics in the planetesimal belts and, by inference, in the planets.

Current Knowledge: Currently, large databases of bright debris disks are available for which *spatially unresolved thermal infrared observations* (spectral energy distributions or SEDs) are available. For a subset of disks *spatially resolved* scattered light or thermal emission images are available (see, e.g., Figure A2.2). For another handful of disks spatially and/or Doppler-resolved gas line detections are available (e.g., Moór et al. 2011, Kóspál et al. 2013, Dent et al. 2014). Mid-infrared spectroscopy of solid state dust features and polarimetric imaging provide additional constraints on dust composition and disk structure (e.g., Perrin et al. 2015).

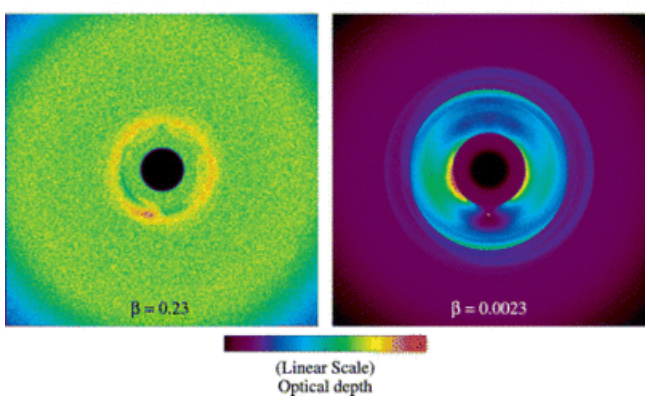

Figure A2.1 Comparison of the optical depths predicted by disk-planet interactions models for a composite cloud formed for a 2 earth-mass planet at 6 au (from Stark & Kuchner 2008). The planet, marked with a white dot, orbits counterclockwise in these images. Left: Optical depth of the smallest particles included in the composite clouds. Bottom right: Optical depth of the largest particles included in the composite clouds. The largest particles dominate the optical depth in a cloud of particles released with a Dohnanyi crushing law.

Sub-questions

1) **Presence, orbits, and masses of unseen planets:** Detailed simulations of debris disk structures and disk-planet interactions provide predictions for the expected disk structures (e.g., Wyatt et al. 1999, 2003; Mouillet et al. 1997; Stark & Kuchner 2008). In a large set of disks complex structures have been observed which can be possible explained via the influence of yet unseen planets (e.g., Schneider et al. 2014); in a very small number of systems disks and planets have been observed together, providing an opportunity to study disk-planet interactions and to validate models.
2) **The orbits and masses of planets seen in the direct images:** With certain direct imaging architectures (e.g., starshades) opportunities for multi-epoch observations may be limited, making it more difficult to verify that point sources are planets and not background sources; and to estimate masses/orbits for the planets from short integrations. Most directly imaged systems are expected to host dust disks, whose structures may be used to verify that the planet candidates imaged are indeed in the system and then to constrain their mass and orbit.
3) **The inclination of the disk/planet system.** An important, but particularly challenging pair of parameters in the planet's orbit determination is the inclination/eccentricity pair, which is partially degenerate and can be difficult to disentangle from observations limited to a handful

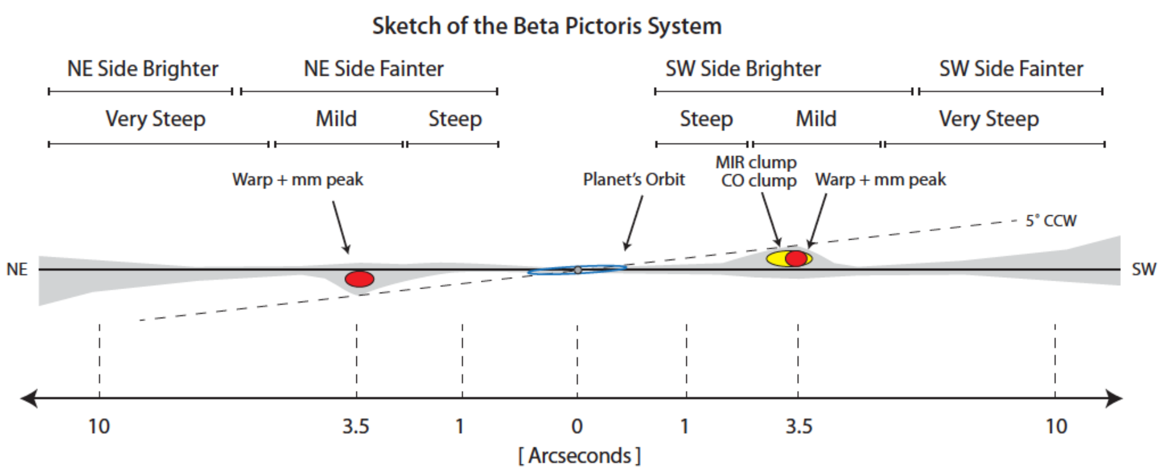

Figure 14. Key structures in the β Pic system, as derived from multi-wavelength imaging.

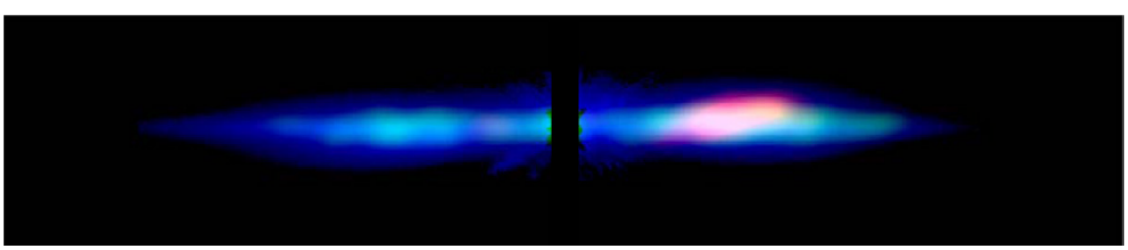

Figure A2.1: Simulations of the structure of the edge-on debris disk around Beta Pictoris correctly predicted the location and masinteractionss of the perturber super-Jupiter Beta Pictoris b (Mouillet et al. 1997). This disk remains the best example of disk-planet. Lower panel: HST/STIS coronagraphic image (blue), ALMA dust continuum (green), and ALMA CO gas emission (red) illustrate the complex structure of the disk (from Apai et al. 2015).

of visits. Resolved debris disks structures can complement measurements of the planet's relative motion to break the degeneracy of inclination/eccentricity. For example, nearly-edge on disks can be recognized even in single-epoch images, which then greatly constrain the available space phase for the planet's orbit.

4) **Formation and dynamical evolution history of the systems:** The mass and position of planetesimal belts can provide powerful constraints on the formation and evolution of planetary systems, including planet migration and/or major orbital rearrangements. For example, the asteroid and Kuiper belts in the Solar System have revealed such orbital rearrangement and potential past instabilities (e.g., Malhotra 1993, Tsiganis et al. 2005). Sensitive time-resolved observations in debris disks also have the potential to identify the aftermath of recent major impacts, dust clumps moving under the influence of radiation pressure, or dust created by planetesimals trapped in resonant structures (e.g., Wyatt , Apai et al. 2015, Boccaletti et al. 2015)

5) **Compositional constraints on the availability of volatiles/organics in the planetesimal belts.** In each system planetesimal belts are leftover reservoirs of some of the material that formed the planets and therefore their composition can provide constraints on the composition of the planets themselves. Of particular interest are the availability of volatiles and organics in the planetesimals, as these are thought to be heavily depleted in the warm, inner disk regions where habitable planets accrete. Organics and volatile content or cover change the optical properties of the dust grains, producing signatures that are detectable in the optical (e.g., Debes et al. 2008) and in the infrared (e.g., Rodigas et al. 2014, 2015).

Complementary Data: Exo-zodiacal disk studies will benefit from s
1) *WFIRST imaging of debris disks:* [input from WFIRST PS team?]
2) ALMA observations of cold debris disks:
3) LBTI observations of the warm debris:
4) JWST observations of warm debris disks:
5) Spitzer surveys of debris disks: Very large and homogeneously analyzed, unresolved debris disk surveys are available that provide a context for bright and massive debris disks as a function of stellar spectral type and age, and presence of known exoplanets (e.g.,).

Questions to SAG15:
1) To what extent could the dust belt structures be used to: a) deduce the presence of lower-mass planets; b) provide constraints on the mass and eccentricity of the directly imaged planets in the system; or c) constrain the dynamical evolution of given planetary systems, i.e., through constraining possible migration histories?

Category B: Questions on Exoplanet Properties

B1. How do rotational periods and obliquity vary with orbital elements and planet mass/type?

Contributors: Daniel Apai, Nicolas Cowan

A planet's rotational state refers to both its obliquity and frequency, or equivalently period. Planetary rotation constrains the formation and angular momentum evolution of a planet, especially when comparing statistical samples of diverse planets. Moreover, the rotation of a given planet impacts its climate through diurnal forcing and Coriolis forces, and contributes to magnetic field generation.

Yang et al. (2013, 2014) showed that the rotation periods of temperate terrestrial planets changes the inner boundary of the habitable zone by a factor of 2 in insolation. Planetary magnetic fields, on the other hand, may be important shields against atmospheric loss. The rotational state of temperate terrestrial planets directly impacts their habitability.

<u>Current status and methods:</u> As of now rotation periods for planets and exoplanets have been determined through four different methods:

a) The dayside map of HD 189733b suggests that this hot Jupiter has zero obliquity (Majeau et al. 2012, de Wit et al. 2012). Although the eastward offset of the hotspot observed on most hot Jupiters (Knutson et al. 2007, 2009, 2012, Crossfield et al. 2010, Cowan et al. 2012) is consistent with equatorial super-rotation on a synchronously-rotating planet (Showman & Guillot 2002), but also with slower winds on a non-synchronous planet (Rauscher & Kempton 2014). In fact, there is a complete degeneracy between the rotation of a gaseous exoplanet and its winds (Cowan & Agol 2011a).

b) *Period of magnetic field's rotation:* The magnetic field is tracing the interior rotation period of the planet, which may be different from the latitude-averaged rotation period measured in the upper atmosphere. In the Solar System Jupiter's and Saturn's rotation periods are defined by the rotation of their inclined (w.r.t. spin axis) magnetic dipoles. For exoplanets, in exceptional cases, the manifestation of inclined magnetic dipoles may be detectable through time-varying auroral emission at UV/optical wavelengths or via modulated synchrotron emission in the radio.

c) *Absorption line width measurements* for directly imaged giant exoplanets (Beta Pictoris b: Snellen et al. 2014). Similar studies for rotational line broadening have been carried out successfully for brown dwarfs (e.g.,). In order to convert the $v\sin i$ into a rotation period, one must know the planet's radius. This method is therefore well-suited for brown dwarfs and giant planets, which are all roughly the size of Jupiter, but could prove problematic for low-mass directly-imaged planets of unknown radius.

d) Rotational photometric/spectroscopic modulations in hemisphere-integrated light for directly imaged exoplanets (Fig. B1.2, Zhou et al. 2016) and planetary-mass brown dwarfs (Biller et al. 2015). Observations of brown dwarfs (planetary mass and more massive), good analogs for directly imaged exoplanets. These observations showed that low-level (~1%) rotational modulations in thermal emission are common (e.g., Buenzli et al. 2014; Metchev et al. 2015), and can be used to measure or constrain rotational periods (e.g., Artigau et al. 2009, Radigan et al. 2012, Apai et al. 2013). Reflected-light observations of Solar System giant planets demonstrated that rotation periods can be measured (e.g., Jupiter: Karalidi et al. 2015; Neptune: Simon et al. 2016).

The latter two techniques may be both applicable for exoplanets directly imaged with next-generation space telescopes. While method b requires high spectral resolution and provides Doppler information, method c requires only high signal-to-noise time-resolved photometry and not strongly wavelength-dependent.

Earth observations: In addition, to exoplanet observations, considerable effort was put into exploring time-revolved observations of Earth, as exoplanet analog. Researchers have used simulated disk-integrated brightness variations of Earth to demonstrate estimate its rotational period, even in the presence of time-varying clouds (Pallé et al. 2008; Oakley & Cash 2009). Likewise, such observations spanning multiple orbital phases constrain obliquity (Kawahara & Fujii 2010, 2011; Fujii & Kawahara 2012, Schwartz et al. 2016, Kawahara 2016). Schwartz et al. (2016) showed that although both latitudinal and longitudinal able inhomogeneities contribute to the obliquity signal, the latter contains more information. In principle, the amplitude modulation of rotational variations at only three orbital phases uniquely identifies a planet's obliquity vector (the obliquity and its orientation with respect to the observer's line of sight). Taking the complementary—frequency modulation—approach, Kawahara (2016) showed that modest signal-to-noise observations spanning most of a planet's orbit could also constrain a planet's obliquity, even if one is agnostic of the planet's albedo map.

Other Solar System planets as exoplanet analogs observations: Overlapping Kepler photometry and Hubble Space Telescope images of Neptune have shown complex time-varying signal whose frequency analysis revealed not only the fundamental rotation rate, but also the level of differential rotation of major mid-latitude cloud features (Simon et al. 2016). Quasi-continuous 20-hour-long two-band optical imaging of Jupiter with the Hubble Space Telescope provided simultaneous high-precision photometry and high-fidelity and high-resolution images (Karalidi et al. 2015). These authors showed that MCMC-based lightcurve modeling can

<u>Questions to SAG15 (B1):</u>

1) *How important are rotation periods for different types of planets?*
2) *To what accuracy should rotation periods be determined? This is ill-defined unless one specifies the expended rotation period a priori. The max dwell time sets an upper limit on the period one can be sensitive to (would like to see >1.5 full rotations), while the exposure time sets a lower limit on the rotation period (need >5 exposures per rotation).*
3) *Connection between planet formation/evolution and angular momentum (Tremaine 1991; Dones & Tremaine 1993; Kokubo & Ida 2007; Miguel & Brunini 2010; Schlichting & Sari 2007)*
4) *Connection between rotation period - magnetic field - stellar wind: implications for atmospheric loss for habitable planets (variety of papers by UR Christensen about scaling laws between planetary mass, rotation, and magnetic dynamo)*

correctly retrieve the position, size, and surface brightness of the dominant features in the lightcurve, such as the Great Red Spot, even from a single rotation.

<u>Science cases and Considerations for different planet types:</u>

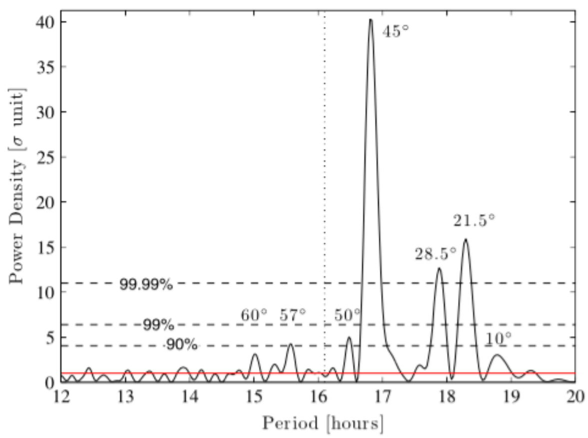

Figure B1.1: Whitened power spectrum from 50-day-long Kepler monitoring of hemisphere-integrated reflected light Neptune, with the most significant peak corresponding to the rotation period. Numbers above some peaks indicate the latitudes on Neptune corresponding to that rotation period based on the zonal velocities. From Simon et al. (2016).

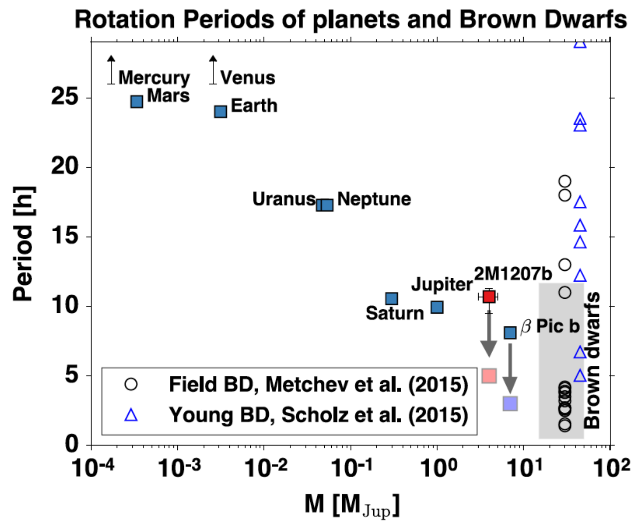

Figure B1.2: Rotation periods provide insights into the properties and formation of planets. A comparison of Solar System planets, directly imaged exoplanets, and brown dwarfs reveals a characteristic mass-dependent rotation rate for massive planets. The arrows shows the expected spin-up due to gravitational contraction. From Zhou et al. (2016).

Gas and Ice Giant Exoplanets: Non-axisymmetrically distributed condensate clouds and hazes (photochemical or other origin) will introduce rotational modulations, both in reflected and in thermal emission (e.g., Simon et al. 2016). In addition, polarimetric modulations introduced by light scattering on heterogeneously distributed dust/haze grains may also be detectable. The rotation periods of gas/ice giants may be useful for constraining their formation/evolution (e.g., Tremaine 1991).

Atmosphere-less Rocky Planets ("Super-Mars"): Rocky planets with very thin or no atmosphere may exists, perhaps as a result of extensive atmospheric loss due to evaporation (Hot Super-Mars), stellar wind stripping, or impact stripping. At pressures lower than water's triple point (6 mbar) liquid water is not stable., even if the planet is otherwise Earth-sized and it is in the habitable zone. For these planets establishing rotational periods may provide insights into the mechanism that led to the complete atmospheric loss.

While atmosphere-less rocky planets would not be suitable for direct measurements of their rotational periods through method c (absorption line width measurements), significant features at the rocky surface would introduced photometric rotational modulations that would be suitable for characterization through method d.

Habitable Planets (Earth-sized or Super-Earths): Rotation periods are important for climate and atmospheric circulation models of habitable planets; for constraining diurnal temperature modulations; and for constraining current and past magnetic field strengths and, indirectly, constraining the atmospheric loss that may have occurred on these planets.

Ongoing observations by the Earth-observing EPIC camera (Kane et al.) will provide an important demonstration of the technique.

Hazy Atmospheres: Planets with thick haze layer may pose a challenge for rotational signal using methods c and d (depending on the wavelengths of observations and the origins of molecular absorption or cloud features studied). Because haze particles —by definition — are small (~0.01 µm), their residence time in the atmosphere will be much longer than the rotational period (t_{res} >> P), which will result in featureless haze layers. As haze particles can be generated at smaller pressure levels and will settle down much slower than larger particles produces by condensation, the featureless haze layers — if optically thick — will mask any heterogenous condensate cloud structure as well as any surface structures. Similarly, optically thick haze layers may cover or weaken the rotationally broadened line profiles in the atmospheres, also limiting the use of Doppler techniques. Therefore, planets enshrouded in thick haze layers are not well suited for rotational studies.

[NBC: I think it would be better to unify the terrestrial and gas giant paragraphs throughout this report. The techniques are not actually any different, and keeping them united helps motivate the work we do on giant planets as testbeds for what we eventually hope to achieve with smaller worlds.]

Obliquity for Earth-like planets and for planets with quasi-permanent features : [methods have been developed for both longitudinal and latitudinal albedo markings]: The obliquity of habitable planets has a major impact on the seasonal and diurnal temperature variations and on their climate in general. Obliquity is much more difficult to determine than the directly observable rotational rate. However, simulated observations demonstrate that it is possible to determine this quantity from high signal-to-noise reflected light lightcurves obtained at multiple orbital phases.

Obliquity for gas giants: For gas giants (with well-constrained radius) combining the rotational period determined from rotational modulations with radial velocity information (line broadening due to rotation) allows constraining or deriving the inclination of the planet (e.g., Allers et al. 2016). Amplitude and frequency modulation of reflected light rotational variation (Schwartz et al. 2016; Kawahara 2016), Fourier spectrum or polarimetry of thermal emission (de Kok et al. 2011; Cowan et al. 2013).

Complementary Observations: Need planetary radius in order to convert rotational broadening into a rotational period. However, if the goal is to know the Coriolis forces, then rotational broadening is sufficient. For the photometric methods that produce a period estimate, on the other hand, the diurnal forcing pops out for free, while the Coriolis forces again require the planetary period. So in general I would say that rotational information is most useful when combined with radius estimates. No complementary observations are required for science results from rotational period measurements, but observations constraining the planetary orbits may be combined with the obliquity and rotational period to constrain the formation history of low-mass planets. Planet mass measurements from radial velocity or astrometry, or gravitational interactions between the planets, can be combined with rotational periods to determine the angular momenta of the giant planets, which may be useful for constraining their accretion history.

<u>Data Required:</u>

B2. Which rocky planets have liquid water on their surfaces? Which planets have continents and oceans?

Contributors: Nick Cowan, Daniel Apai, Ravi Kopparapu, Jim Kasting

Relevance: Water is not a biosignature itself, but the presence of liquid water is required for life as we know it. And life as we know it is probably the only kind of life that we may be able to identify remotely. Liquid water is not the only factor required for planetary habitability, but it is arguably the most important one. Thus, liquid water is a "habitability signature". Establishing which habitable zone planets have liquid water on their surfaces provides an important context for EXOPAG SAG16, which focuses on biosignatures, but will rely on SAG15 for habitability signatures and characterization of habitable planets.

The traditional habitable zone (HZ) is defined in terms of surface liquid water (Kasting et al. 1993). Three distinct methods have been proposed to search for large bodies of liquids (**oceans**) on the surface of a planet:

Rotational color variability (Ford et al. 2001; Cowan et al. 2009; Kawahara & Fujii 2010, 2011; Cowan et al. 2011). Oceans are darker and have different colors than other surface types on Earth, so the time variations in color of a spatially unresolved planet can betray the presence of liquid water oceans. This method relies on there being longitudinal inhomogeneities in the planet's surface composition.

Polarization (Zugger et al. 2010, 2011). Oceans are smoother than other surface types and thus polarize light. For idealized scenarios, the phase variations in polarization are significant, but the same authors found that in practice the effect of oceans is masked by Rayleigh scattering, clouds and aerosols. Observations of polarized Earthshine, however, imply that rotational variations in polarization may be useful in detecting oceans (Sterzik et al. 2012).

Specular reflection (Williams & Gaidos 2008; Robinson et al. 2010). Oceans are also able to specularly reflect light, especially at crescent phases. The signal-to-noise requirements for phase variations are not as stringent as for rotational variations since the integration times can be much longer: weeks instead of hours. However, Robinson et al. (2010) showed that clouds not only mask underlying surfaces, but forward scattering by clouds mimics the glint signal at crescent phases, while atmospheric absorption and Rayleigh scattering mask the glint signature. They proposed using near-infrared opacity windows to search for glint, but this would only be possible if the effects of clouds could be accurately modeled for exoplanets. However, Cowan, Abbot & Voigt (2012) showed that crescent phases statistically probe the least-illuminated and hence coldest regions of a planet, insofar as these planets have ice and snow in their coldest latitudes, then this latitude albedo effect acts as false positive for ocean glint.

Although the faces of extrasolar planets will not be spatially-resolved in the foreseeable future, their rotational and orbital motions produce detectable changes in color and brightness. Ford, Seager & Turner (2001) used simulations of Earth to show that the changing colors of its disk-integrated reflected light encode information about continents, oceans, and clouds. The inverse problem—inferring the surface geography of a planet based on time-resolved photometry—is much more daunting than the forward problem and at first blush looked intractable.

Much progress has been made on the "exo-cartography" inverse problem since the seminal work of Ford, Seager & Turner (2001). The rotational *color* variations of a planet can be used to infer the number, reflectance spectra, and longitudinal locations of major surface types

(Cowan et al. 2009, 2011; Cowan & Strait 2013). Meanwhile, the rotational and orbital color variations of an unresolved planet can be analyzed to create a 2-dimensional multi-color map—equivalently a 2D map of known surfaces (Kawahara & Fujii 2010, 2011; Fujii & Kawahara 2012).

Additional methods may be used to deduce the probably presence of liquid water on the surface of a potentially habitable planet *without detecting liquid on the surface*:

1) Test whether partial pressure of water vapor reaches saturation and/or
2) Identify clouds made of liquid water droplets (and not water ice).

B2 - Additional Comments:

Comments from SAG15 Team / Telecon 2:
From Jim Kasting:
The key question for me concerns the availability of liquid water on the surfaces of rocky planets orbiting other stars. Water is not a biosignature itself, but the presence of liquid water is required for life as we know it. And life as we know it is probably the only kind of life that we may be able to identify remotely. Liquid water is not the only factor required for planetary habitability, but it is arguably the most important one.

Related observables: 1) orbital distance. It is critical to determine the semi-major axes of rocky exoplanets because this plays a key role in determining whether they can support liquid water on their surfaces. Note that this likely requires multiple revisits to each planetary system of interest. On TPF-C, we assumed 5-6 revisits per system. 2) Gaseous CO2 and H2O. Both of these gases are potentially observable at near-IR wavelengths. CO2 is even easier to observe in the thermal-IR, but that requires a different kind of direct imaging mission.

Other comments:
Consensus: Important question.
Multiple people: Presence of water may be constrained through measurements other than atmospheric spectroscopy; rotational phase mapping, for example, could be important.
RK: Determining P-T profile and presence of water clouds would also be important/ useful.
SDG: This question connects well to SAG16, where we study biosignatures. Liquid water on the planetary surface is a habitability signature, which is not studied in SAG16; SAG16 will rely on SAG15 for this context.

Analysis of simulated exo-earth observations was used to demonstrate that rotational phase mapping (time-resolved observations of hemisphere-integrated reflected light from the planet) can reveal the types and distribution of surfaces. Equipped with additional data on the color/ spectra of the features and the physical conditions on the planetary surface may be used to identify surface features as oceans and continents.

1. Determining the semi-major axis of a planet from the star is critical as it may determine the presence of liquid water on the surface. How many visits per system are needed by a direct imaging mission to determine an accurate orbital distance?

2. CO2 and H2O have strong features in the near-IR. What wavelength range in the near-IR do we need to cover to observe these features?

B3. What are the origins and composition of clouds and hazes in ice/gas giants and how do these vary with system parameters?

All Solar System planets with an atmosphere also harbor cloud and/or haze layers. Clouds and hazes influence the pressure-temperature structure of the atmosphere, its emission and transmission spectrum, as well as the albedo of the planets. Particles or droplets that make up clouds primarily form through condensation and grow via further condensation and/or particle collisions. With grains sizes that may range from a micron to ~millimeter cloud particles/droplets have short settling time and are typical at higher atmospheric pressures (~1 bar).

Haze particles (typically <0.1 micron in size) often form via photochemistry-drive or charged-particles-driven chemical reactions in the upper atmospheres (<1 bar); with long residence times these particles often introduce large optical depths to upper atmospheres.

From an observational perspective clouds and hazes may also used as tracers of atmospheric dynamics (circulation, mixing, turbulence). Presence of haze or cloud layers may also mask the presence of specific atmospheric absorbers even if present at large abundances at pressures higher than the particle layer.

Exoplanets are expected to harbor a large variety of condensates: for solar compositions these include Ca-Ti-oxides, silicates, metallic iron, sulfides, CsCl and KCl, H_2O, NH_4HS, NH_3 (for a review see …).

Current Knowledge: Condensate clouds have been observed in brown dwarfs with a broad temperature range (e.g., Metchev et al. 2015) and for hot jupiters (e.g., Sing et al. 2016). High-altitude haze layers have been observed for transiting planets ranging from hot jupiters to super-earths (Kreidberg et al. 2014) and possibly for earth-sized planets (de Wit et al. 2016), as well as for brown dwarfs (Yang et al. 2015). Observational constraints on the origin of condensate clouds include:
a) Pressure range where they reside ; b)

Understanding the composition of cloud- and haze-forming particles is an important step in developing physical/chemical models for exoplanets.

Questions to SAG15:

Questions to SAG15:
AD: 1) How challenging are the very different methods described here relative to each other?
2) How are they best carried out?

1) What data can constrain particle size distribution, pressure levels, composition?
2) What fundamental parameters (composition, temperature, surface gravity?) are expected to have significant impact on cloud/haze formation and properties?

Notes: Question revised in Telecon 3. Additional, related question (B5) added.

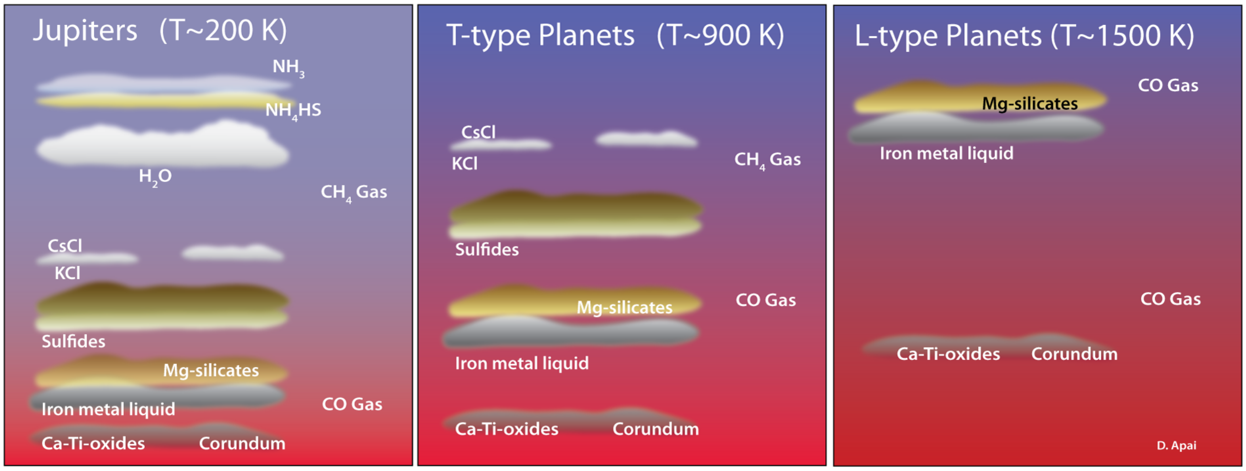

Figure B3.1 Condensate clouds predicted for the upper atmospheres of planets of different temperature. After Lodders (2003).

B5. How do photochemistry, transport chemistry, surface chemistry, and mantle outgassing effect the composition and chemical processes in terrestrial planet atmospheres (both habitable and non-habitable)?

Authors: Daniel Apai, Nick Cowan

Answering this question will also provide a context for interpreting biosignatures in habitable planets discussed in SAG16.

Question added in Telecon 3.

Question to SAG16:
1) What planetary constraints are important for the interpretation of biosignatures?

Earth has a unique surface character among Solar System worlds. Not only does it harbor liquid water, but also large continents. An exoplanet with a similar appearance would remind us of home, but it is not obvious whether such a planet is more likely to bear life than an entirely ocean-covered waterworld—after all, surface liquid water defines the canonical habitable zone. Recent work suggests that 1) Earth's bimodal surface character is critical to its long-term climate stability and hence is a signpost of habitability (Abbot, Cowan & Ciesla 2012; Foley 2015), and 2) we will be able to constrain the surface character of terrestrial exoplanets with next-generation space missions (Ford, Seager & Turner 2001 …recent stuff by Cowan, Fujii, Kawahara). Recent reviews of geochemical cycling: Cowan (2015), Foley & Driscoll (2016).

Category C Questions: Processes

C1. What processes/properties set the modes of atmospheric circulation and heat transport in exoplanets and how do these vary with system parameters?

Authors: Daniel Apai, Nick Cowan, Ravi Kopparapu

Atmospheric circulation plays a key role in redistribution energy in exoplanets' atmospheres. Depending on wind speed, rotational velocity, insolation, latent heat released during condensation, and other system parameters a range of atmospheric circulation regimes are expected on planets that can be studied with direct imaging missions.

For potentially habitable exoplanets atmospheric circulation will determine the day-night heat differential and the equator-pole temperature difference. Understanding the presence and size of Hadley cells can also provide important insights into how water vapor (or other condensibles) may be distributed in habitable planets.

Understanding atmospheric circulation in habitable exoplanets is an important component in establishing a correct climate model for them.

As of now, atmospheric circulation has been probed in the Solar System planets and a small

sample of brown dwarfs, hot jupiters and lower-mass exoplanets (Abe et al. 2011; Wordsworth et al. 2011; Leconte et al. 2013a; Yang et al. 2013; Zhang and Showman 2014; Kataria et al. 2014; Wolf & Toon 2015; Kopparapu et al. 2016). The nature of the atmospheric dynamics depends upon how thick an atmosphere the planet has, the rotation rate of a planet, the distance of the planet from the star and several other factors. A more comprehensive study of different atmospheric circulation regimes of exoplanets remain unexplored.

Using time-resolved observations and rotational phase mapping techniques atmospheric circulation may be constrained.

Questions to SAG15:

Questions to SAG15:

1) To what level can the atmospheric circulation be constrained for different types of planets?
2) What hypotheses / toy circulation models should be tested for gas giants?
3) What hypotheses / toy circulation models should be tested for habitable super-earths / earths?
4) What data type and cadence is required or best suited for characterizing circulation?

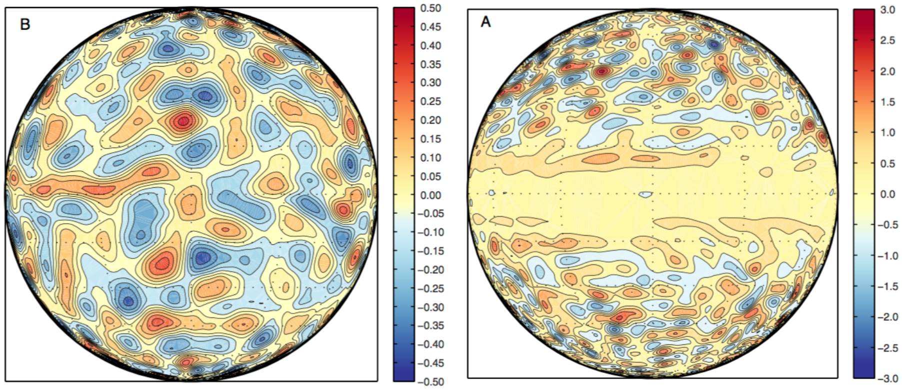

Fig C1.1 Depending on the relative importance of rotational speed, wind speed, and vertical heat transport, simple models predict two different regimes of circulation for giant planets: vortex-dominated (left) and jet-dominated (right). From Zhang & Showman (2014).

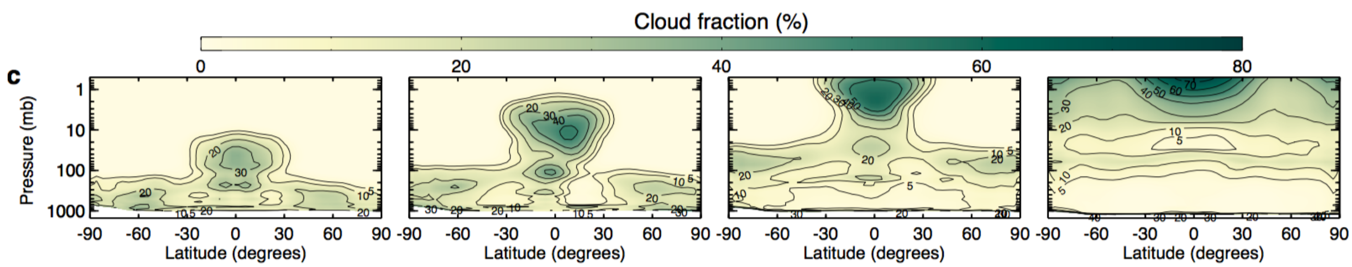

Figure C1.2 Moist/water-rich atmosphere simulations from Wolf & Toon(2015). The four panels indicate the amount of cloud fraction on a planet at different insolations (or alternately how close to an inner edge of the HZ a planet is located). From left to right, the solar insolation varies S0 (current Earth insolation), 10% of S0, 12.5% S0 and 21% of S0. This is for an Earth-size planet around a Sun-like star.

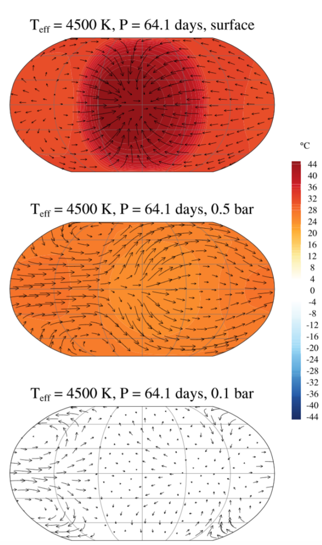

Figure C1.3 Temperature and horizontal wind vectors at the surface, 0.5 bar, and 0.1 bar levels for an Earth-mass planet in a slow-rotating regime near the inner edge of the habitable zone around a K-dwarf. Slowly rotating planets develop subs-stellar clouds that increase the albedo of the planet. Inflow along the equator and from the poles into the substellar point at the center is also shown. From Kopparapu et al. (2016).

C2. What are the key evolutionary pathways for rocky planets and what first-order processes dominate these?

C2 - Additional Comments:

From Nick Cowan: WHY DO PLANETS TURN OUT THE WAY THEY DO? In other words, which aspects of planet formation (mass, spin, composition) impact which aspects of planetary atmospheres and climate? This is a classic nature vs nurture problem. Maybe the most important determinant of a planet's evolution is the final major impact, or its star's UV flux, or maybe it is the planet's volatile content... or maybe it is first-order stochastic with only second-order correlations to the factors above. Another way to think about the effect of nurture is the extent to which planets exhibit hysteresis. If Earth and Venus traded locations, would the new cooler Venus end up looking more Earth-like in the long run, and vice versa.

Stephen Kane: The evolution is perhaps understood as "Atmospheric evolution".

However, there are lot of important differences between Earth and Venus beyond their location in the Solar System: their rotational periods and magnetic fields are very different.

We should make it clear that the focus is on fundamental, important parameters. We could rephrase the question as "What are the first order effects that determine evolutionary pathways?" Perhaps just irradiation is important, but maybe also composition, etc.

C3. What types/which planets have active geological activity, interior processes, and /or continent-forming/resurfacing processes?

Planetary interior processes and geological activity play an important role in coupling Earth's atmosphere to its crust and providing a long-term stabilizer for Earth's climate. The source of Earth's atmosphere and volatiles are mostly products of outgassing after the loss of the primary atmosphere.

Developing reliable climate models to determine the habitability of potentially habitable planets will likely require assumptions on the geological activity and the level of coupling between the planet's crust and atmosphere.

Interior processes are obviously very difficult to probe via low signal-to-noise and spatially unresolved remote sensing.

Current Knowledge: Currently no methods are capable of probing geological activity in exoplanets and our knowledge is limited to a range of possible activity levels predicted by various extrapolations of the activity levels of rocky planets in the Solar System.

Possible ideas includes:

1) Detection of atmospheric absorbers that can be attributed to volcanic release, and deducing the level of volcanic activity.
2) Using land-mass distribution to place constraints on continent-forming processes.
3) Other methods?

Data Requirements

This section identifies the type and quality of data ideal or required to answer the individual science questions discussed in Section 2.

Summary of data requirements

Science Questi-ons	Optical			Near-Infrared			Mid-IR		Num. Targets
	Phot.	Spec.	Pol.	Phot.	Spec.	Pol.	Phot.	Spec.	
A1									
A2									
A3									
A5									
B1									
B2									
B3									
B4									
C1									
C2									
C3									
C4									

SAG15 Charter

Future direct imaging missions may allow observations of flux density as a function of wavelength, polarization, time (orbital and rotational phases) for a broad variety of exoplanets ranging from rocky sub-earths through super-earths and neptunes to giant planets. With the daunting challenges to directly imaging exoplanets, most of the community's attention is currently focused on *how* to reach the goal of exploring habitable planets or, more specifically, how to search for biosignatures.

Arguably, however, most of the exoplanet science from direct imaging missions will not come from biosignature searches in habitable earth-like planets, but from the studies of a much larger number of planets *outside* the habitable zone or from planets within the habitable zone that do not display biosignatures. These two groups of planets will provide an essential context for interpreting detections of possible biosignatures in habitable zone earth-sized planets.

However, while many of the broader science goals of exoplanet characterization are recognized, there has been no systematic assessment of the following two questions:
1) What are the most important science questions in exoplanet characterization *apart* from biosignature searches?

2) What type of data (spectra, polarization, photometry) with what quality (resolution, signal-to-noise, cadence) is required to answer these science questions?

We propose to form SAG15 to identify the key questions in exoplanet characterization and determine what observational data obtainable from direct imaging missions is necessary and sufficient to answer these.

The report developed by this SAG will explore high-level science questions on exoplanets ranging from gas giant planets through ice giants to rocky and sub-earth planets, and — in temperatures — from cold (~200 K) to hot (~2,000 K). For each question we will study and describe the type and quality of the data required to answer it.

For example, the SAG15 could evaluate what observational data (minimum sample size, spectral resolution, wavelength coverage, and signal-to-noise) is required to test that different formation pathways in giant planets lead to different abundances (e.g. C/O ratios). Or the SAG15 could evaluate what photometric accuracy, bands, and cadence is required to identify continents and oceans in a habitable zone Earth-sized or a super-earths planet. As another example, the SAG15 could evaluate what reflected light data is *required* to constrain the fundamental parameters of planets, e.g. size (distinguishing earth-sized planets from super-earths), temperature (cold/warm/hot), composition (rocky, icy, gaseous), etc.

SAG15 will not attempt to evaluate exoplanet detectability or specific instrument or mission capabilities; instead, it will focus on evaluating the *diagnostic power* of different measurements on key exoplanet science questions, simply adopting resolution, signal-to-noise, cadence, wavelength coverage as parameters along which the diagnostic power of the data will be studied. Decoupling instrumental capabilities from science goals allows this community-based effort to explore the science goals for exoplanet characterization in an unbiased manner and in a depth beyond what is possible in a typical STDT.

EXOPAG SAG15 Draft Report – Feb 5, 2016

We envision the SAG report to be important for multiple exoplanet sub-communities and specifically foresee the following uses:

1) Future STD teams will be able to easily connect observational requirements to missions to fundamental science goals;

2) By providing an overview of the key science questions on exoplanets and how they could be answered, it may motivate new, dedicated mission proposals;
3) By providing a single, unified source of requirements on exoplanet data in advance of the Decadal Survey, the science yield of various missions designs can be evaluated realistically, with the same set of assumptions.

Our goal is to carry out this SAG study by building on both the EXOPAG and NExSS communities.

We aim to complete a report by Spring 2017 and submit it to a refereed journal, although this timeline can be adjusted to maximize the impact of the SAG15 study for the ongoing and near-future STDTs and other mission planning processes.

Synergy with a potential future SAG proposed by Shawn Domagal-Goldman: While the SAG proposed here will include studies of habitable zone rocky planets, it will focus on planets without significant biological processes. A future SAG may be proposed by Shawn Domagal-Goldman to explore biosignatures; if such a SAG is proposed, we envision a close collaboration on these complementary, but distinct problems.

SAG15 Timeline and Process

This section records the SAG15 timeline and explains how the report was assembled and identifies the methods through which community input was solicited and collected.

SAG15 Website: http://eos-nexus.org/sag15

Telecon 1: December 15, 2016 (Minutes)

Telecon 2: March 2, 2016 (Minutes)

Telecon 3: April 6, 2016 (Minutes)

The minutes, agenda, documents, and slides for each telecon are available at the SAG15 website: http://eos-nexus.org/sag15/