SAG15 DRAFT REPORT

SCIENCE QUESTIONS FOR
DIRECT IMAGING EXOPLANET MISSIONS

DANIEL APAI AND THE SAG15 TEAM

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Contents

1. The SAG15 Team

Chair: Daniel Apai, University of Arizona (apai@arizona.edu)

Members:

Travis Barman, University of Arizona
Alan Boss, Carnegie DTM
James Breckenridge, Caltech
David Ciardi, IPAC/Caltech
Ian Crossfield, University of Arizona
Nicolas Cowan, McGill University
William Danchi, NASA GSFC
Shawn Domagal-Goldman, NASA GFSC
Caroline Morley, Lick Observatory
Glenn Schneider, University of Arizona
Nicolas Iro, University of Hamburg
Stephen Kane, San Francisco State University
Theodora Karalidi, University of Arizona
James Kasting, Penn State University
Ravikumar Kopparapu, NASA GSFC
Patrick Lowrence, IPAC/Caltech
Avi Mandell, NASA GSFC
Mark Marley, NASA Ames
Michael McElwain, NASA GSFC
Nikku Madhusudhan, Cambridge University
Charley Noecker, JPL
Peter Plavchan, Missouri State University
Aki Roberge, NASA GSFC
Leslie Rogers, University of Chicago
Adam Showman, University of Arizona
Arif Solmaz
Philip Stahl, NASA MSFC
Karl Stapelfeldt, JPL
Mark Swain, JPL
Margaret Turnbull, SETI Institute

With Additional Input From:

Yuka Fujii, NASA GISS
Markus Kasper, European Southern Observatory
NExSS Community, Breakout session

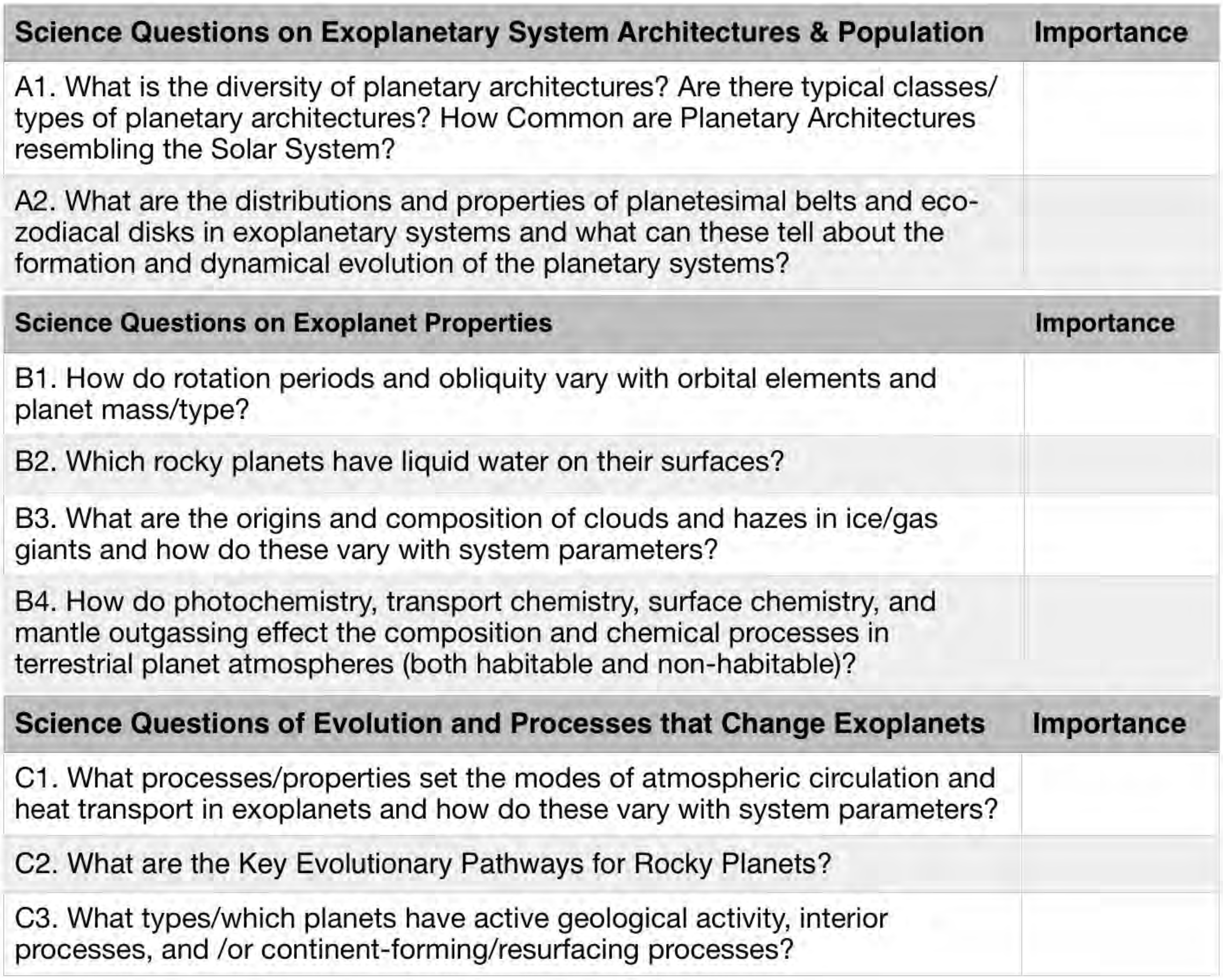
2. Introduction

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.

3. 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. 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?	

4. Exoplanetary System Characterization

4.1. 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: The diversity of planetary system architectures is expected to reflect the range of possible pathways of planetary system formation and evolution.

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.

Sub-questions:

- *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.
- *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.
- *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.

4.1.1. Complementary Non-Imaging Data

- *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.

- *Microlensing:* Statistical constraints from the WFIRST-Microlensing survey will provide important context for the frequency of medium-separation low-mass planets.
- *Ground-based adaptive optics imaging:* These observations may be capable of discovering giant exoplanets and providing positions at additional epochs.
- *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.

Observational Requirements (draft)
Sample size:
Observations:

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?
M. Kasper: ELT direct imaging will provide a lot of info about small planets at small angular separations, together with GAIA information, planetary system architectures will be quite well explored in 10-20 years.

4.2. 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:

- The presence, orbits, and masses of embedded, yet unseen planets.

- The orbits and masses of planets seen in the direct images, but for which orbits are not known.

- The inclination of the disk/planet system.

- Formation and evolution history of the system, including migration and orbital rearrangements of the planets.

- Compositional constraints on the availability of volatiles/organics in the planetesimal belts and, by inference, in the planets.

4.2.1. 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 Dopent et al.

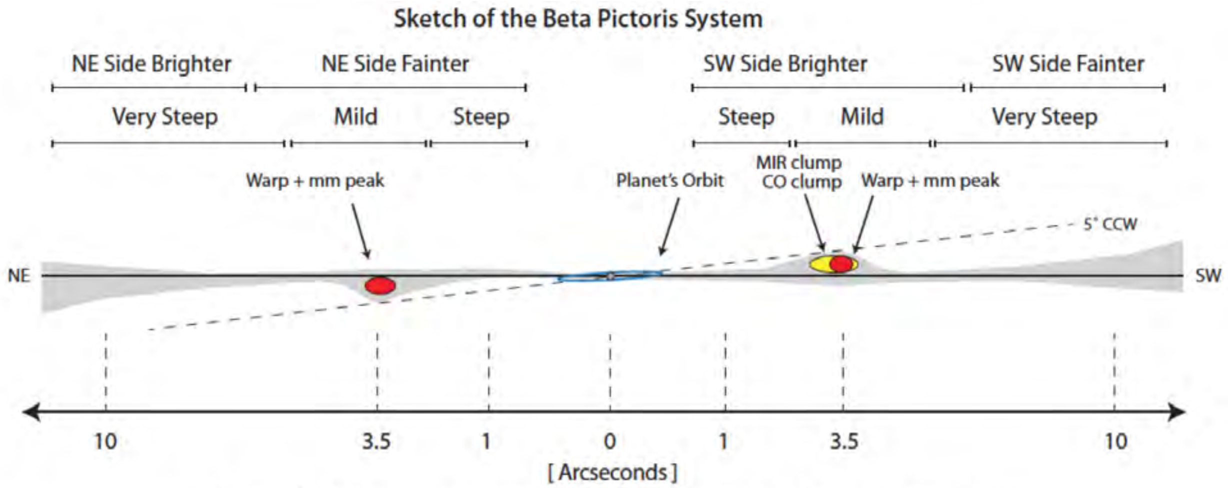


Figure 14. Key structures in the β Pic system, as derived from multi-wavelength imaging.

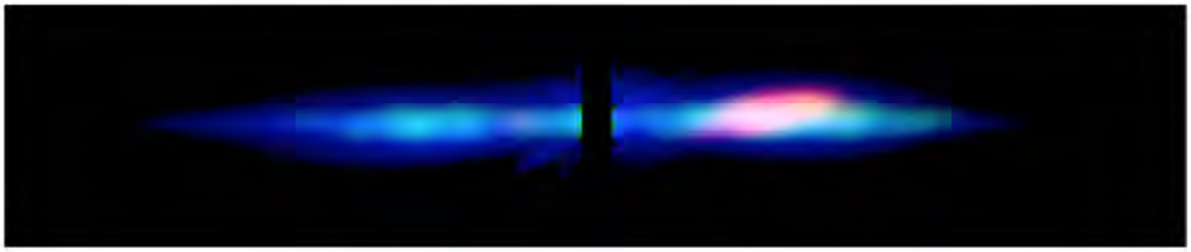


Fig. 1.— Simulations of the structure of the edge-on debris disk around Beta Pictoris correctly predicted the location and masinteractionss of the perturber super-Jupiter Beta Pictoris b (Mouillet et al. 1997). This disk remains the best example of disk-planet. Lower panel: HST/STIS coronagraphic image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

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).

4.2.2. Sub-questions

Presence, orbits, and masses of unseen planets: Detailed simulations of debris disk structures and disk-planet interactions provide predictions for the expected disk structures (see Fig. 2, Wyatt et al. e.g., 1999; Wyatt e.g., 2003; Mouillet et al. e.g., 1997; Stark & Kuchner e.g., 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 (see, e.g., Fig. 1).

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.

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 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.

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 2003; Apai et al. 2015; Boccaletti et al. 2015).

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 at optical and infrared wavelengths (e.g., Debes et al. 2008; Ballering et al. 2016; Rodigas et al. 2014).

Observational Requirements (draft)
Sample size:
Observations:

4.2.3. Complementary Data

Exo-zodiacal disk studies will benefit from:
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:
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?

5. Exoplanet Characterization

5.1. 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 its circulation through the Coriolis force, and contributes to magnetic field generation.

For example, Yang et al. (2014, 2013) showed that the rotation periods of temperate terrestrial planets changes the inner boundary of the habitable zone by a factor of two in insolation. Furthermore, planetary magnetic fields may be important shields against atmospheric loss. As these examples illustrate the rotational state of temperate terrestrial planets directly impacts their habitability.

5.1.1. Methods used to Measure Rotational Periods

Rotational periods for planets and exoplanets have been determined through four different methods:

a) Phase Curve for Irradiated Planets: For some close-in synchronously rotating giant exoplanets the orbital/rotational phase modulation is detectable in the combined light of the star+planet system. The modulation also allowed longitudinal mapping the planets: For example, 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. 2012b) 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 2011).

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 rotational period measured in the upper atmosphere. In the Solar System Jupiter's and Saturn's rotational 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. Recent detections of modulated radio emission from nearby brown dwarfs (e.g. Kao et al. 2016) suggests that very deep radio-wavelength observations of extrasolar giant planets may also be used in the future to establishing their rotational periods.

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. Reiners & Basri 2008). In order to convert the observed $v \ sin \ i$ 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 approximately the size of Jupiter, but could prove problematic for lower-mass directly-imaged planets of unknown radius.

d) Rotational photometric/spectroscopic modulations in hemisphere-integrated light for directly imaged exoplanets (Fig. 4, 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 ($\sim$ 1%) rotational modulations in thermal emission are common (Buenzli et al. 2014; Metchev et al. 2015), and can be used to measure or constrain rotational periods and study cloud properties (e.g., Artigau et al. 2009; Radigan et al. 2012; Apai et al. 2013). Similarly, reflected-light observations of Solar System giant planets have also been used to demonstrated that rotational periods and their cloud covers can be characterized (e.g., Jupiter: Karalidi et al. 2015; Neptune: Simon et al. 2016).

Observational Requirements (draft)
Sample size:
Observations:

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.

5.1.2. Science Cases

Habitable Planets (Earth-sized and Super-Earths): Rotation rates are an im-

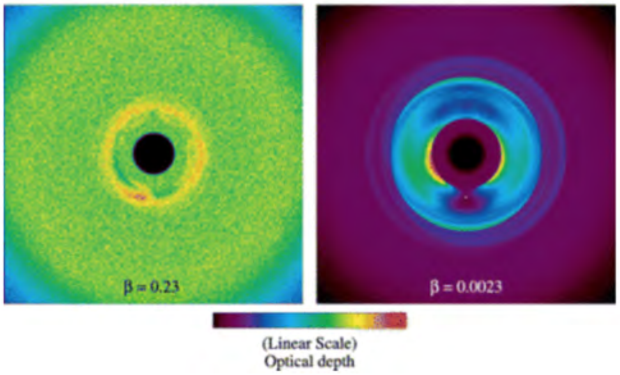


Fig. 2.— Comparison of the optical depths predicted by disk-planet interactions models for a composite cloud formed for a 2 earth-mass planet at 6 au (from Stark & Kuchner 2008). The planet, marked with a white dot, orbits counterclockwise in these images. Left: Optical depth of the smallest particles 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.

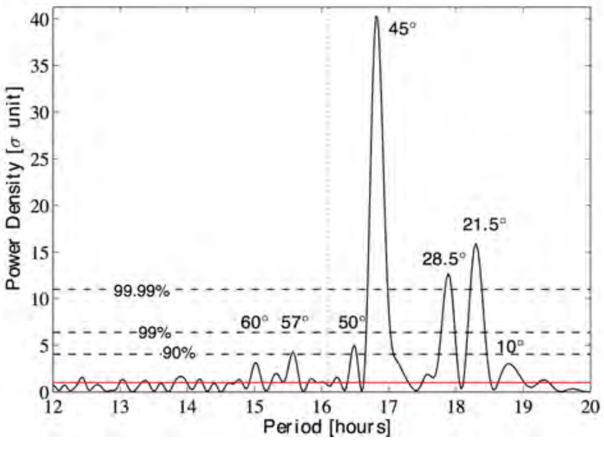


Fig. 3.— Whitened power spectrum from 50-day-long Kepler monitoring of hemisphere-integrated reflected light Neptune, with the most significant peak corresponding to the rotation period. Numbers above some peaks indicate the latitudes on Neptune corresponding to that rotation period based on the zonal velocities. From Simon et al. (2016).

portant parameter for climate and atmospheric circulation models of habitable planets: they constrain diurnal temperature modulations, determine the strength of the Coriolis force, influence current and past magnetic field strengths and geometry, and indirectly constrain the atmospheric loss that may have occurred on these planets. Comparative studies of dynamo-generated magnetic energy densities in Solar System planets, the Sun, and rapidly-rotating low-mass stars show a correlation between the magnetic field strengths and the density and bolometric flux of the objects (e.g., Christensen et al. 2009). These studies argue for a scaling relation, based on Ohmic dissipation, where the field strength is only weakly sensitive to rotation rate, but the rotational rate fundamentally impacts the magnetic field geometry (bipolar vs. multi-polar, Christensen 2010). Furthermore, rotational rates also carry information about the accretion history of the planets and, in particular, about the size distribution of the planetary building blocks (e.g., Schlichting & Sari 2007).

In addition, the obliquity of habitable planets also 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.

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.

Atmosphereless Rocky Planets: Rocky planets with very thin or no atmosphere may exists (analogous to a "super-Mars" or a "dry Earth", an Earth-like planet that lost is atmosphere and water). Such planets may form as result of extensive atmospheric loss due to evaporation (Hot super-Mars), stellar wind stripping, or impact stripping (e.g., Schlichting et al. 2015). 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 inside the habitable zone. The ability to measure rotational periods for these planets may provide important insights into the mechanism that led to the complete atmospheric loss. Atmosphereless rocky planets are suitable for direct measurements of their rotational periods as prominent albedo features at the rocky surface will introduce photometric rotational modulations.

Fujii et al. (2014) used albedo-map generated lightcurves and, where available, observed photometric variations to explore the geologic features detectable on diverse Solar System bodies with minor or no atmospheres (Moon, Mercury, the Galilean moons, and Mars). The study included the evaluation of the light curves and the features that are detectable at wavelengths ranging from UV through visible to near-infrared wavelengths, and also explored the accuracy required to determine the orbital periods of these bodies. Figure 6 provides an example for the wavelength-dependence of the rotational variability amplitudes in different bodies.

Gas and Ice Giant Exoplanets: The rotational periods of gas/ice giants may also be useful for constraining their formation and evolution (Tremaine 1991) and important for understanding their atmospheric circulation. 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. Currently, rotational rate estimates exist for close-in exoplanets (assumed to be equal to their orbital periods) and a few measurements exist for directly imaged exoplanens and planetary-mass brown dwarfs. The rotational angular momenta of close-in exoplanets (on synchronous rotation) is reset by tidal interactions and no longer carries information on the intrinsic angular momenta of the objects. In contrast, angular momenta of non-synchronously rotating exoplanets (such as those probed via direct imaging) carry information about their formation and angular momentum evolution. Photometric modulations have been measured in two near-infrared filters for the ∼4–6 M_{Jup} exoplanet 2M1207b (Zhou et al. 2016) and led to a rotational period measurement of $10.7^{+1.2}_{-0.6}$ h. CO absorption line rotational broadening measurements for the 10–13 M_{Jup} planet β Pictoris suggests a v sin i=15 km/s, which, assuming an equatorial viewing geometry, suggests a very similar rotational period. Similarly to these young exoplanets, photometric variations were used to measure the rotational periods of unbound young planetary mass-objects (Biller et al. 2015) and very low-mass brown dwarfs (Scholz et al. 2015). The picture emerging – based on the very limited data – suggests that super-jupiter exoplanets and low-mass brown dwarfs start with similar angular momentum and during their evolution their rotate rate increases, converging to the extrapolation of the Solar System mass-period relationship (see Figure 4).

A direct imaging mission capable of obtaining moderately high signal-to-noise ratio photometry on giant exoplanets can study possible trends between planet mass, semi-major axis, and rotational period.

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 & Cowan 2015; Kawahara 2016), Fourier spectrum or polarimetry of thermal emission (de Kok et al. 2011; Cowan et al. 2013).

A Note on 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.

5.1.3. Complementary Observations

For methods that measure rotational velocity the knowledge of planetary radius is required 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. In general 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.

5.1.4. Science Value of Independently Measured Planet Masses and Radii

Periodicity in photometric variations is a direct measure of the rotational period, i.e., rotational period measurements do not require mass measurements. However, verifying the predicted trend between angular momentum, orbital period, mass (which potentially constrains the formation history) requires mass and radius measurements or uncertainties. *Giant Planets:* Radii for mature giant planets will be close to one Jupiter radius, but masses may vary by an order of magnitude. Masses may be derived from atmospheric modeling that includes a fit for surface gravity.

Radii and masses of rocky planets vary *more* than those of giant planets: mass may vary by a factor of ∼20 (from Mars to super-Earths): while rotational periods alone will be important and useful for atmospheric circulation models, mass and/or radius measurements would yield important additional science: mass measurements would allow exploring trends between formation mechanisms and angular momentum; and radius estimates (even from mass-radius relationships) would allow calculating Coriolis forces from rotational periods, significantly constraining the atmospheric circulation models.

Observational Requirements (draft)
Sample size:
Observations:

Questions to SAG15 (B1):
How important are rotation periods for different types of planets?
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). Connection between planet formation/evolution and angular momentum (Tremaine 1991; Dones & Tremaine 1993; Kokubo & Ida 2007; Miguel & Brunini 2010; Schlichting & Sari 2007)?
Kasper: ELT HCI + HRS will allow us to study rotation periods, sample will be small - not sure about statistical relevance

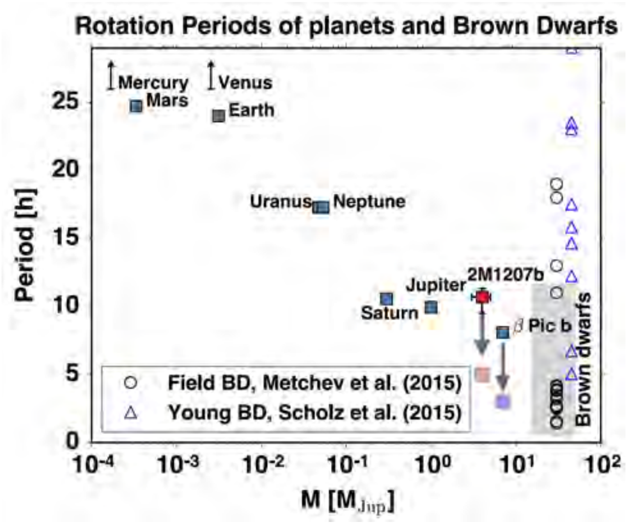


Fig. 4.— Rotation periods provide insights into the properties and formation of planets. A comparison of Solar System planets, directly imaged exoplanets, and brown dwarfs reveals a characteristic mass-dependent rotation rate for massive planets. The arrows shows the expected spin-up due to gravitational contraction. From Zhou et al. (2016).

Property	**Optimal Wavelengths Range**	**Expected Amplitude**	**Acceptable Wavelengths Range**	**Expected Amplitude**	**Baseline or Num. Observations**	**Re**
Rotational Period						
Earth/Super-Earth					3-30 h (1 Period)	
Super-Mars	0.9	25%	0.5-10	10-35%	3-30 h (1 Period)	7
Ice/Gas Giant	5	15%	0.3-5.0	3%	3-20 h (1 Period)	8
Obliquiuty						
Earth/Super-Earth						
Super-Mars	0.9	25%	0.5-1.0	10-35%	3 x 1 Period	7
Ice/Gas Giant	5	15%	0.3-5.0	3%	3 x1 Period	8

Table 1: My caption

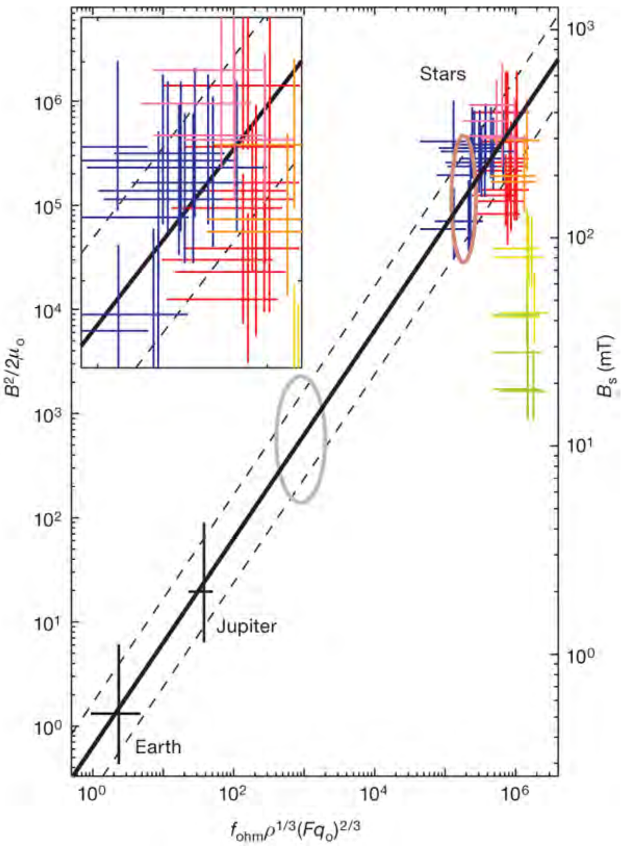


Fig. 5.— The comparison between Earth, Jupiter, and stars shows that the magnetic energy density (in the dynamo) strongly correlates with a function of density and bolometric flux (here both in units of J m^{-3}). The bar lengths show estimated uncertainty rather than formal error (Supplementary Information). The stellar field is enlarged in the inset. Brown and grey ellipses indicate predicted locations of a brown dwarf with 1,500 K surface temperature and an extrasolar planet with seven Jupiter masses, respectively. From Christensen et al. (2009).

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

Relevance: Water is not a biosignature itself, but the presence of liquid water is required for life as we know it. 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.

Our understanding of distribution of water in exo-earths is very incomplete: Currently, water detections in extrasolar systems are limited to protoplanetary disks (), hot jupiters, and white dwarfs polluted by tidally disrupted minor bodies; however, no direct or indirect observations exist of water in extrasolar habitable zone Earth-like planets or even super-Earths exist.

In the following we will discuss two different pathways for identifying liquid water on Earth-like habitable zone planets: 1) via the detection of oceans; and 2) via the inference of water vapor in the atmosphere close to saturation pressure.

5.2.1. Detecting Oceans

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 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. Ford et al. (e.g. 2001); Cowan et al. (e.g. 2009); Fujii et al. (e.g. 2010); Kawahara & Fujii (e.g. 2011,?).

Polarization (e.g. 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 et al. (2012a) 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 et al. (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 et al. (2001). The rotational color variations of a planet can be used to infer the number, reflectance spectra, surface area, and longitudinal locations of major surface types Fujii et al. 2010, 2011; 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 (Fujii et al. 2010; Kawahara & Fujii 2011, 2010; Fujii & Kawahara 2012.

5.2.2. Inferring Liquid Water

Additional methods may be used to deduce the probable presence of liquid water on the surface of a potentially habitable planet without detecting an ocean: *1) Test whether partial pressure of water vapor reaches saturation*, and/or
2) Identify clouds made of liquid water droplets (and not water ice).

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.

5.2.3. Related Measurements:

1. **Orbital semi-major axis** of a planet 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. **Presence of Greenhouses gases** and water vapor in the atmosphere: CO_2 and H_2O have strong features in the near-IR.

Observational Requirements (draft)
Sample size:
Observations:

Comments on B2):
Kasper: Another possibility may be that reflected light is very highly polarized (as oceans have low albedo - Stam et al. ?

5.3. 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 $< 0.1\mu$m 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 Marley & Robinson e.g., 2015).

Current Knowledge: Condensate clouds have been observed in brown dwarfs with a broad temperature range (Buenzli et al. 2014; 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, in prep.), 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) Grain size distribution; c) Longitudinal-vertical structure; d) Evolution of cloud cover.

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

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?

Solar System Gas Giants 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 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.

Observational Requirements (draft)
Sample size:
Observations:

Questions to SAG15:
1) How challenging are the very different methods described here relative to each other?
2) How are they best carried out?
Kasper: ELT: A Jupiter analague (1Rj, 5AU) will just be observable (c 1e-9). Neptune / Uranus analogues cannot be seen with an ELT.

5.3.1. Science Value of Independently Measured Planet Masses and Radii

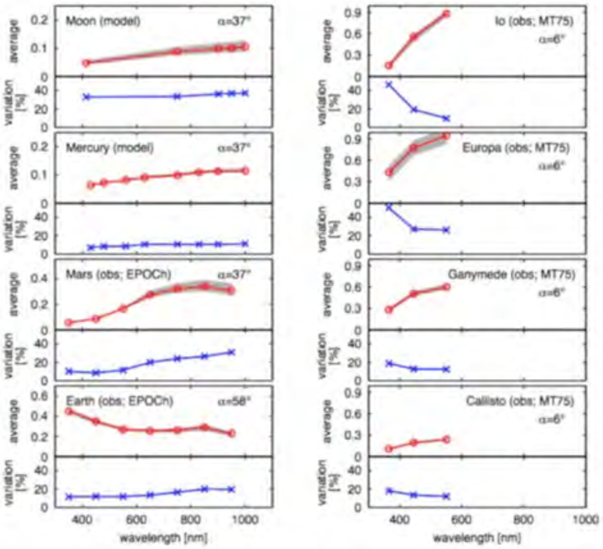


Fig. 6.— Albedo and its variations as a function of wavelengths for Solar System bodies with minor or no atmosphere. From Fujii et al. (2014).

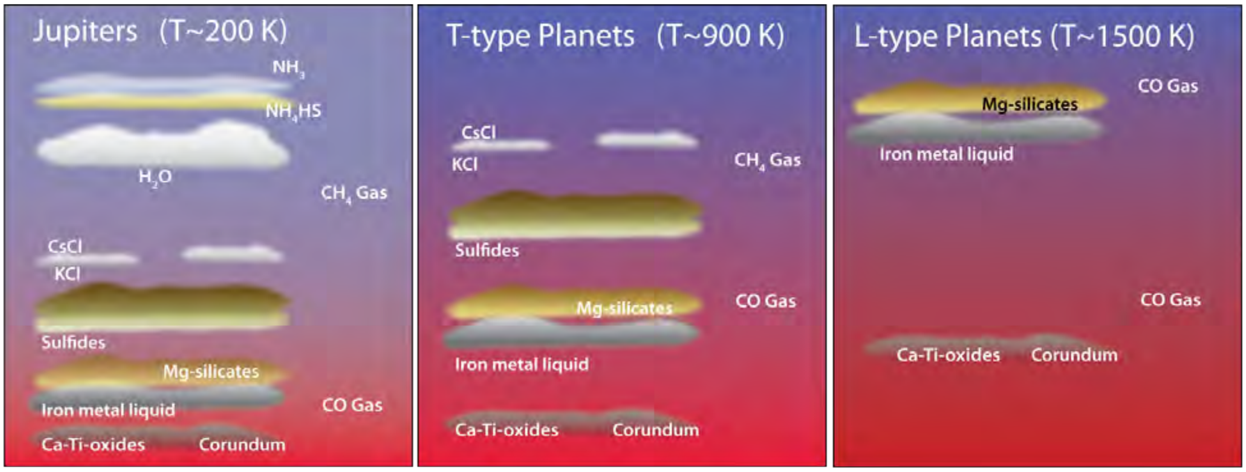


Fig. 7.— Condensate clouds predicted for the upper atmospheres of planets of different temperature. By D. Apai, after Lodders (2003).

6. Exoplanetary Processes

6.1. 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 exoplanet atmospheres. Depending on typical wind speeds, rotational velocity, insolation, latent heat released during condensation, and other system parameters different 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 (see Figs 9 and 10, Yang et al. 2013; Leconte et al. 2013; Abe et al. 2011; Wordsworth et al. 2011; Zhang & Showman 2014; Kopparapu et al. 2016; Kataria et al. 2014; Wolf & Toon 2014). 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:

To what level can the atmospheric circulation be constrained for different types of planets?

What hypotheses / toy circulation models should be tested for gas giants?

What hypotheses / toy circulation models should be tested for habitable super-earths / earths?

What data type and cadence is required or best suited for characterizing circulation?

Observational Requirements (draft)

Sample size:

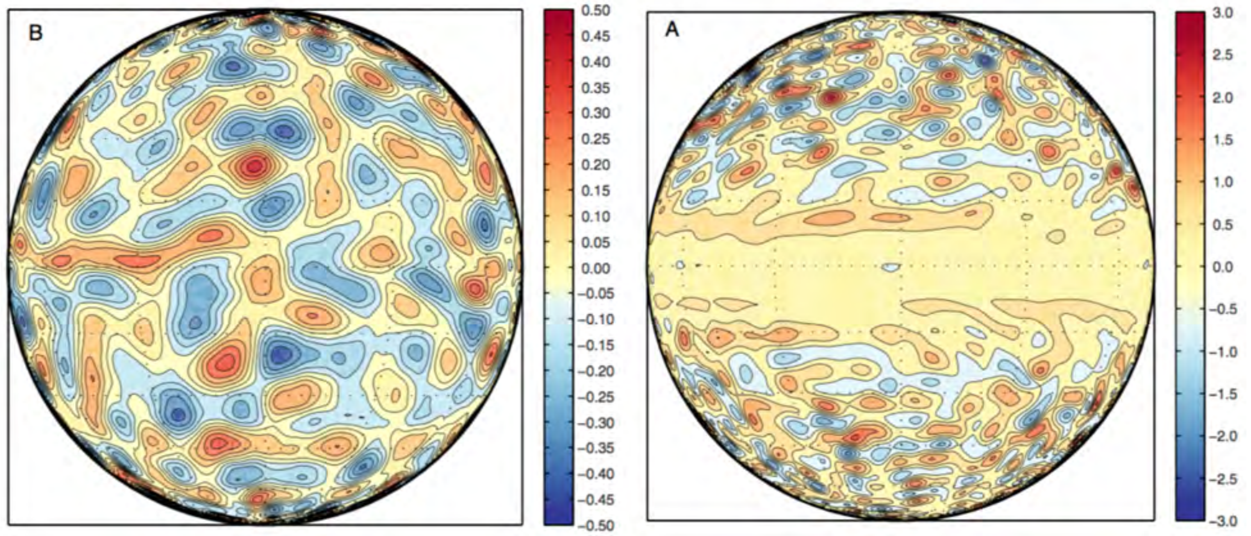


Fig. 8.— Depending on the relative importance of rotational speed, wind speed, and vertical heat transport, simple models predict two different regimes of circulation for giant planets: vortex-dominated (left) and jet-dominated (right). From Zhang & Showman (2014).

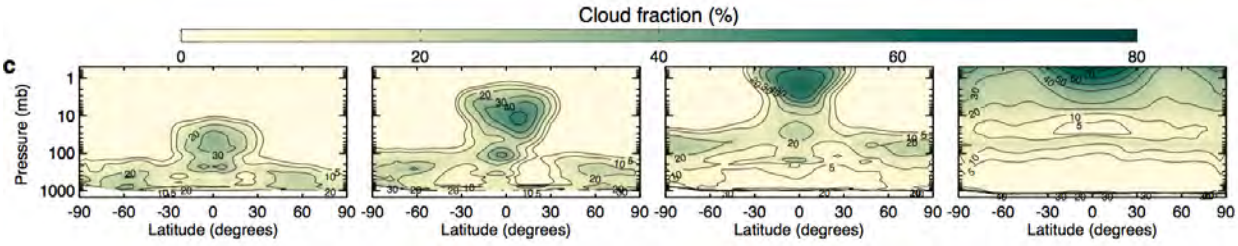


Fig. 9.— Moist/water-rich atmosphere simulations from Wolf & Toon(2014). The four panels indicate the amount of cloud fraction on a planet at different insolations (or alternately how close to an inner edge of the HZ a planet is located). From left to right, the solar insolation varies S0 (current Earth insolation), 10% of S_0, 12.5% S_0 and 21% of S_0. This is for an Earth-size planet around a Sun-like star.

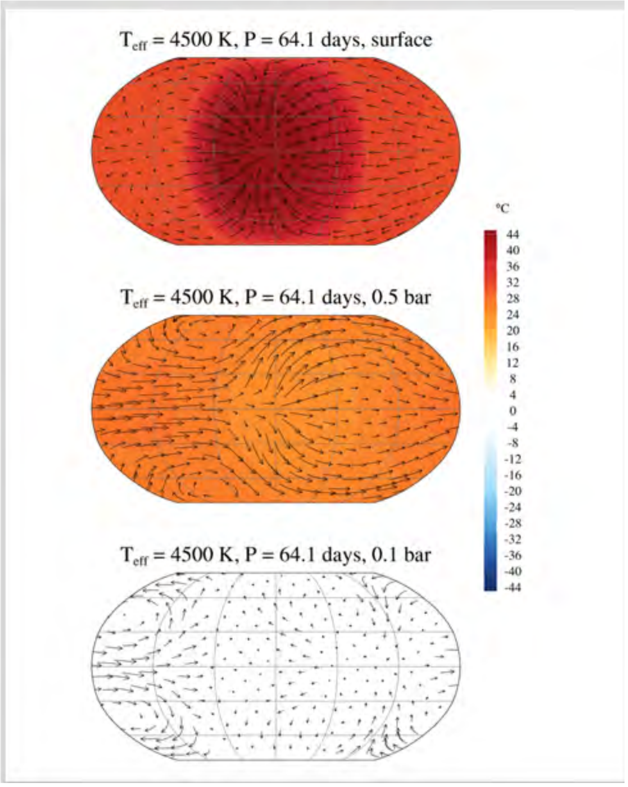


Fig. 10.— Temperature and horizontal wind vectors at the surface, 0.5 bar, and 0.1 bar levels for an Earth-mass planet in a slow-rotating regime near the inner edge of the habitable zone around a K-dwarf. Slowly rotating planets develop subs-stellar clouds that increase the albedo of the planet. Inflow along the equator and from the poles into the substellar point at the center is also shown. From Kopparapu et al. (2016).

Observations:

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

Contributors: Nick Cowan, Daniel Apai

The two earth-sized rocky planets in the Solar System, Earth and Venus, likely have started with very similar initial mass, orbit, and composition, but their evolutionary paths have strongly diverged. Mars, although substantially different in its mass and orbit, has again followed a different evolutionary trajectory, even though it is thought that surface conditions at the early Mars, at least temporarily or episodically, may have resembled the early Earth. With the large number of rocky planets that may be observable with a capable future direct imaging mission the range of evolutionary histories of planets could be explored.

The questions naturally emerge: What key evolutionary pathways exist for rocky planets and what factors determine which of these pathways a given planet will follow?

Attractors and Divergence in the Phase Space of Rocky Planet Evolution: It is reasonable to describe the momentary state of a given rocky planets with a set of n fundamental parameters and explore the evolution of the planet in this n-dimensional phase space. Each planet's history and future evolution is thought of as a trajectory. Fundamental parameters could include, but not be limited to, planet mass, radius, atmospheric pressure scale height, orbital parameters, atmospheric composition, magnetic field strength, etc. Which trajectory a planet follows will depend not only in its momentary location in the phase space, but also by the effect of a set of feedback loops (both positive and negative) as well as on a few environmental variables (e.g., stellar luminosity and incident optical and UV flux).

When describing planet evolution in such a manner, several obvious questions are identified: *1) How sensitive are the trajectories to initial parameters and/or perturbations to the system? 2) What is the importance of a planet's past, e.g., which volumes of the phase space are uni-directional (e.g., irreversible water loss)? 3) Are there preferred evolutionary end-states ('attractors') or is the surface defined by coeval planets smooth? 4) What is the importance of quasi-monotonic evolution driven by a small number processes vs. random walk driven by a multitude of competing processes?*

Exploring the past history and current state of rocky planets allows the system-level study of rocky planet evolution and will be essential for understanding the occurrence rate of truly earth-like planets and to place the physical processes that drive planet evolution on

Earth to the broader context of exo-earths.

6.2.1. Science Value of Independently Measured Planet Masses and Radii

Is the science goal achievable without precise mass measurements? Yes, a medium or large sample of rocky exoplanets for which most of the other key parameters are known would likely suffice to establish the topology of the phase space.

Would the science goal benefit greatly from precise mass measurements? Yes, precise mass measurements would significantly contribute to the understanding of the planets' properties. In case the phase space is highly complex and its projection to a lower-dimensional (observed) phase space does not allow the identification of the key processes that drive the evolution, expanding the projected phase space by a new dimension (mass) may break the degeneracy between different processes that lead to similar evolutionary outcomes.

Observational Requirements (draft)
Sample size: medium to large (>15)
Observations: characterization of the planets: atmosphere pressure and composition, orbital parameters, bulk composition, surface temperature estimate, stellar parameters and past evolution;

Comments: Solicit input from: Robert Boschia, Valerio Lucarinia, Salvatore Pascalea (2013); William Moore, Adrian Lenardic, Dorian Abbot, Dan Fabrycky

To explore: Toy model for testing hypothesis of smooth distribution vs. attractors

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

Contributors: Stephen Kahn, Daniel Apai, Nick Cowan

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.

The influence of volcanism on planetary climate is most clearly understood for the case of Earth. On geologic timescales, continental crust production participates in the stabilization of the Earth's climate through its role in carbonate weathering feedback. Chemical weathering of silicate minerals on land in the presence of water causes the slow removal of CO_2 from the atmosphere, which is eventually deposited on the ocean floor as carbonate compounds. Without the continual re-injection of new CO_2 by volcanoes, the atmospheric stock of CO_2 would be slowly depleted. However, the rate of CO_2 removal by silicate weathering is temperature dependent, so that in the presence of a steady source of volcanic CO_2, weathering interacts with the greenhouse properties of CO_2 to produce a negative feedback on planetary temperature. This interaction, whereby warmer conditions lead to increased drawdown of CO_2 and a consequent weakening of the greenhouse effect (and vice versa), is believed to play an important role in stabilizing planetary temperatures in the presence of a main-sequence star which is increasing in luminosity over Ga timescales. It is because of this process that it has been argued that volcanism and geological activity are necessary conditions for sustained life on a planet.

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.

Studies of terrestrial climate and volcanism focus primarily on the effects of volcanism on surface temperature, which we are unlikely to be able to estimate for most exoplanets. However, volcanically forced anomalies in surface temperature are coupled to anomalies in emission temperature, which can be targeted for follow-up observations. Thus, if volcanism can be identified on an exoplanet it may represent the most promising method for estimation of climate sensitivity outside of the Solar System.

The distinctive effect of volcanic eruptions on the transmissivity of atmospheres is related to the force of their explosions. Typically, processes on Earth that produce aerosols in the atmosphere affect only the troposphere. Aerosols are quickly washed out of the troposphere by rain, and thus do not have a sustained impact on atmospheric transmissivity. Many small eruptions don't reach the stratosphere, however the largest explosive volcanic material can, in contrast, inject SO_2 directly into the stratosphere, where it reacts to form sulphate aerosols.

Because the stratosphere is very dry, these aerosols can persist in the stratosphere for several years, until they are removed by the natural overturning circulation of the stratosphere (Robock et al. 2007). Stratospheric air rises in the tropics and then migrates towards the pole where it sinks. Because of this, aerosols from tropical eruptions typically persist in the stratosphere for about two years, while aerosols from high-latitude volcanism persist for only one year (Robock et al. 2007; Tingley et al. 2014).

Previous work shows a link between exoplanet compositions and stellar compositions (e.g., Rogers & Seager 2010) such that stellar compositions can be used to approximate the composition of exoplanet interiors. Stars in exoplanetary systems show a wide variation in composition (Hinkel et al. 2014). In particular, some composition parameters with large variability such as Mg:Si ratios, are likely to have a first order effect on the minerals that compose exoplanetary interiors and thus the melting behavior, magma composition generated from these planetary mantles, and their volatile solubility. Certain compositional components, such as alkalis, have also been shown to greatly increase the H_2O solubility (e.g., Behrens & Zhang 2001; Larsen & Gardner 2004) in natural melts, and highlight the necessity of measuring volatile solubility behavior across a broad range of melt compositions. Magmatic volatile solubility is highly dependent on temperature, which also varies with mineralogy. For example, we hypothesize that planets with bulk mantle compositions that are dominated by pyroxene and feldspar type minerals (Mg:Si<1) will have lower melting temperatures and thus higher H_2O solubility than planets dominated by olivine.

On Earth, in addition to the pressure- and compositional-dependence of volatile solubility in magmas, the explosivity of a given eruption is dependent on the overall volatile concentration (dominated by H_2O and CO_2), magma supply rate, vent geometry, and source pressure of the magma body (e.g., Wilson 1980; Papale & Polacci 1999; Mason et al. 2004). The most explosive eruptions on Earth tend to be those at convergent plate boundaries where there are abundant volatiles involved in magma genesis sourced from the subducting plate, and some types of intraplate volcanism where interactions with reservoirs of volatiles in the crust produce highly explosive caldera eruptions. In addition, flood basalts and other volumetrically large outpourings of magma common in a planets early history may be a significant source of atmospheric volatiles (Black et al. 2012). As such, the lack of tectonics on exoplanets does not preclude extreme volcanism that would likely produce detectable signatures.

O'Neill et al. (2013) provides a recent review of plate tectonics in Earth and Venus and its sensitivity to radioisotope abundances.

6.3.1. Geological Activity and Plate Tectonics on Extrasolar Rocky Planets

The extrapolation of models of planetary evolution and plate tectonics to extrasolar rocky planets is challenging. A particularly relevant question is how plate tectonics may operate in super-Earths: on one hand, the higher heat flux (due to their intrinsically higher mass-to-surface ratio) should lead to stronger mantle convection (e.g., Valencia et al. 2007; van Heck & Tackley 2011). On the other hand, based on a visco-elastic models of mantle convection and crust formation, O'Neill & Lenardic (2007) find that increasing the planet's radius (and mass) will decrease the ratio of driving-to-resistive forces (see Fig. 11), which reduces the likelihood of mobile plate tectonics in super-Earths and argues for the stagnant lid (or episodic tectonics) in these planets.

Furthermore, for a given planet models also suggest time-dependence and sensitivity to initial conditions: the thermal state of the post-magma ocean mantle is a key parameter that determines the subsequent evolution of the planet (possibly but not necessarily through i) hot stagnant-lid, ii) plate tectonics, then to iii) cold stagnant lid regime). Depending on the planet's transition from the magma ocean stage different evolutionary paths are possible and there may only be a limited time available for Earth-like plate tectonics O'Neill et al. (2016).

6.3.2. Observational Methods

While major geological processes usually unfold on timescales not accessible to large-distance remote sensing, the *results* of these processes are detectable and, in some cases, may be unambiguously identifiable. For example, in the case of Earth the presence of multiple large land-masses and oceans (detectable via time-resolved observations, e.g., Cowan et al. 2009) reveals that a continent-forming process acts on timescales shorter than water-driven land erosion and provides a characteristic scale for the continental plates. Another Earth-based example is the accumulation of atmospheric absorbers characteristic volcanic outgassing (e.g., SO_2: Kaltenegger & Sasselov 2010). Other, non-Earth-like, planets may offer other detectable signatures of geological activity.

In the following we briefly discuss four representative possibilities:

- i) Continents and Oceans from Surface Maps
- ii) Atmospheric Absorbers from Volcanic Outgassing
- iii) Planetary-Scale Surface Mineralogy
- iv) Cloud formation as Tracer of Topography and Erosion

Continents and Oceans from Surface Maps: Simulated observations of Earth as an exoplanet demonstrate that with appropriate rotational- and orbital phase-resolved precision,

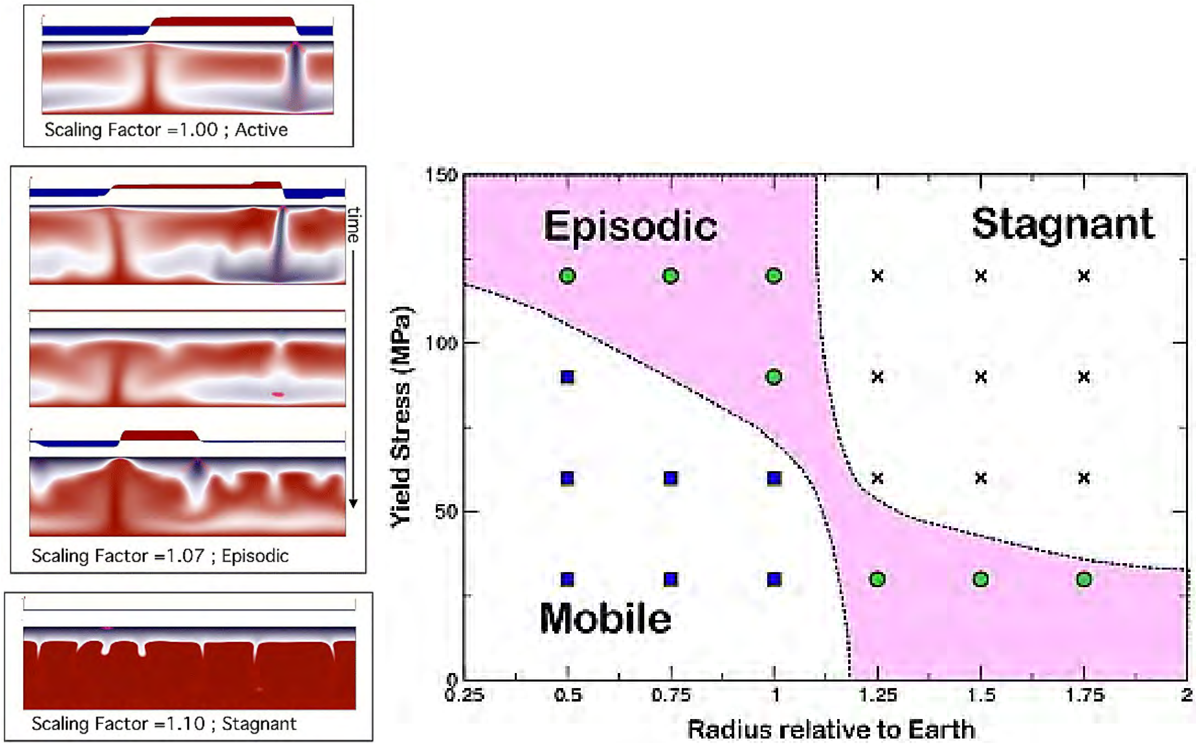


Fig. 11.— Convection as a function of stellar radius and Byerlee-style pressure-dependent yield stress. The models include internal heating, a constant friction coefficient, and gravity matching the planetary mass. Larger radius results in greater buoyancy forces, but also increased fault strength due to increased pressure. Thus planets with larger radii again tend to be in an episodic or stagnant regime, depending on the absolute yield stress. From O'Neill & Lenardic (2007).

multi-band photometric data can be use to identify the presence and one-dimensional and two-dimensional distribution of oceans and landmasses (see also Section 5.2.1, Cowan et al. e.g., 2009; Fujii et al. e.g., 2010; Fujii & Kawahara e.g., 2012. In a planet where large bodies of liquid water (an ocean) is present, a hydrological cycle is active, and land masses (continents) are detected, land erosion is arguably must occur; timescales for the erosion can be estimated based on terrestrial measurements. The existence of the continents demonstrates that the time-scale of continent-formation is comparable or faster than their erosion. Based on a simplified model of water cycling and continent formation Cowan & Abbot (2014) argues that continents and oceans may be common even among super-earths with high abundances of water. Such first-principle-based models may be combined with the scales of oceans and continents derived from observations to test whether active continent formation (e.g., plate tectonics) is required for a given planet.

Water Clouds as Tracer of Topography Similarly to the previous Pallé et al. (2008)

Planetary-scale Surface Geology Fujii et al. (2014) used albedo-map generated lightcurves and, where available, observed photometric variations to explore the geologic features detectable on diverse Solar System bodies with minor or no atmospheres (Moon, Mercury, the Galilean moons, and Mars). The study included the evaluation of the light curves and the features that are detectable at wavelengths ranging from UV through visible to near-infrared wavelengths, and also explored the accuracy required to determine the orbital periods of these bodies. Figure 6 provides an example for the wavelength-dependence of the rotational variability amplitudes in different bodies.

Amplitude variations at the level of 5–50% have been reported introduced by features of diverse nature (volcanism, space weathering, planetary weathering, impact excavation, tectonic deformation). In some cases data with the appropriate wavelength coverage can be used to identify some of these features or narrow down the possible origins.

Volcanic Outgassing

6.3.3. Complementary Datasets

We identify three complementary datasets that are critically important for modeling the interior and activity of extrasolar rocky planets:

- *Stellar abundances:* a proxy for the relative refractory elemental abundances that may be present in the planet; may be used to identify outlier systems in terms of elemental abundances

- *Composition of giant planets in the system:*
- *Stellar/system age:* to constrain the evolutionary state of the planets (heat flux and time available for volatile loss and resurfacing processes)
- *Mass and radius of the planet:* fundamental physical parameters with major impact on energy budget and force balances; and constrains the bulk composition

6.3.4. Science Value of Independently Measured Planet Masses and Radii: Very High

Exploring the planetary-scale geophysics of rocky planets will likely be among the most challenging aspects of characterizing extrasolar rocky planets. Yet, understanding the geophysics and interior activity of these planets may well turn out to be essential for correctly and robustly interpreting atmospheric biosignatures. The rocky planet's mass is one of the most fundamental parameter that influences heat flux, pressure, and horizontal forces acting on the lithosphere. Given the sensitivity of plate tectonics models to planet mass, it is likely that determining the planet mass with a precision of ∼10% is required for establishing a robut geophysical model.

7. Data Requirements

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

Appendix

A. 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.

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.

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