Victoria Meadows (University of Washington/NExSS/ExoPAG Past Chair)
ExoPAG: The Exoplanet Program Analysis Group

- Community-based group that solicits and coordinates community analysis and input for Exoplanet Exploration Program objectives
- Organizes and runs Study Analysis Groups and Science Interest Groups
- Provides findings of analyses to the NASA Astrophysics Division Director (Paul Hertz) that are made publicly available to the community.
- Enables direct regular communication between NASA and the community, and within the community, through open meetings, e-mail and other mechanisms
- Open to all interested scientists. Next meetings: July 2020, January 2021
- Currently proposing to initiate an ExoPAG Science Interest Group on Exoplanet/Solar System Synergies (SIG3) to:
  - Provide opportunities for ongoing discussions on Exo/SS comparative planetology
  - Explore how exoplanet and Solar System missions can benefit from each other.
Over 4000 exoplanets are known

Most exoplanets have either size or mass known, semi-major axis, orbital shape. Some have density, spectra. Exoplanets therefore have the potential to provide a large statistical sample and broad context for SS planets.
Solar System planets can serve as exoplanet analogs

Solar System planets could serve as “exoplanets in our backyard” to provide insights into environments and processes for some of the most common types of exoplanets.
Exoplanets inform a diversity of planets and processes

At the same time, the exoplanet population provides a diversity of planetary types that are NOT found in the Solar System, and the evolution and nature of these bodies may inform Solar System science as well.

However, at the moment, there is NOT a lot of overlap between the populations of exoplanets we are finding, and Solar System planets.

This makes it harder to put our Solar System in context, but we have made some inroads...
Are we weird? Yes. (Jupiters may be rare!)

Although the exoplanet population and the Solar System population have very little overlap at the moment....

Extrapolations from current surveys suggest that Jupiters are rare, with only about 10% of solar type stars and 3% of M dwarfs harboring giants inside of 10 AU.

….but the region between 3 and 10 AU is still to be fully explored

The WFIRST microlensing survey will explore this range of phase space, with sensitivity extending to terrestrial planets orbiting M dwarf stars.

C. Dressing
Jupiters have a large impact on volatile delivery to forming terrestrials

Models suggest that the presence of a Jovian, and any migration of the Jovian during and after the planet formation process can greatly impact system architecture and the distribution and delivery of volatiles.

Observations of exoplanet density in multiplanet systems can help to unravel the importance of a Jovian to other planets in the system.
Terrestrial-class and sub-Neptune-class exoplanets are common

Due to recently improved size estimates, the size boundary between terrestrials and mini-Neptunes is known for close-in planets orbiting FGK dwarfs.

- Planets with $R < 1.5 \text{ R}_\text{Earth}$ are more likely to be terrestrial, and appear to be a distinct population.

- This "Fulton gap" is likely due to photoevaporation, and hints at a very different mechanisms for "terrestrial" planet formation for these close-in planets.

For periods less than 100 days and Sun-like stars ONLY

Fulton et al., 2017
Neptune-mass planets show an astonishing diversity of densities. Exoplanets of Neptune mass can exhibit a 3 orders of magnitude range of bulk densities, which leads to a wide range of inferred interior structures and bulk composition.

How does such diversity arise: formation history, thermal/chemical evolution, or other processes? Could be informed by orbital elements and planet composition.

An improved understanding of Solar System planet interiors (e.g., ice giants) and outgassed atmospheres (e.g., Venus) could help inform exoplanet studies.
Exoplanet multi-planet systems are not like the Solar System

Although planetary systems are common, we do not know if the solar system architecture is common.

Current observations are biased towards co-planar planets with short periods.

These close-in systems are susceptible to gravitational interactions and tidal heating... with the Jovian moons providing potential analogs for processes.

Campante et al., 2015
Many Techniques Could be Used to Observe Terrestrial Exoplanets. And There Are Many Ways to Observe an Exoplanet.
Transiting planets will dominate near-term observations.
But this will be quite a challenge!
JWST will favor observations of planets orbiting smaller M dwarf stars.

Small planets in the HZ produce better transmission spectra around M dwarf stars. TRAPPIST-1 is not much bigger than Jupiter!
We have characterized a diversity of giant worlds

Initial characterization attempts show a diversity of environments

Transmission spectra of ten hot Jupiters with HST showed clear/cloudy atmospheres, strong stratospheric inversions, vs no stratosphere, and a range of abundances ("metallicities").
And exo-Neptunes

Possibly trends in composition with size (smaller planets having lower H fraction "higher metallicity").

Amplitude of water absorption at 1.4 μm increases with irradiation (Teq)

Crossfield & Kreidberg, 2018

Wakeford et al., 2017
De Wit et al., (2016; 2018) used HST to observe TRAPPIST-1 planets and ruled out an H$_2$-rich atmosphere on all but g.

Delrez et al., (2018) observed Spitzer bands. There are inconclusive, but suggestive, of CO$_2$.

Observations suggest atmospheres are not H$_2$-dominated and cloud-free (e.g. Wakeford et al., 2019). Lab/modeling suggest atmospheres are also unlikely to be H$_2$-rich and cloudy (Moran et al., 2018).

And we stand on the brink of exoterrestrial characterization
Highly-irradiated terrestrials, Venus’ sisters, will be observed first.

Hot Earths orbiting M dwarfs (e.g. GJ1132b and TRAPPIST-1 b, c and d) may undergo a similar, but longer volatile-loss process than that experienced by Venus (Schaeffer et al., 2016).
The star’s super-luminous pre-main-sequence phase may drive a Venus-like runaway greenhouse early on. The star will then DIM... This did not and will not happen to our Venus.

What happens to a cooled Venus is a fascinating new avenue for exploration of terrestrial evolution, with data to help discriminate theories expected in the next 5 years.

M dwarf terrestrials, may undergo a very different evolutionary sequence
Evolution could generate uninhabitable planets in the HZ

Lincowski et al., (2018)

Atmospheric composition can be strongly altered by evolution.

Surface temperature depends strongly on atmospheric composition.

If Venuses were created during the ocean loss process for TRAPPIST-1, they could extend through the entire HZ.

T-1b may be cloud free!
Formation and Migration May Form Volatile-Rich Terrestrials

- TRAPPIST-1’s long resonant chain suggests migration from more distant birth orbits (Luger et al., 2017).

- TRAPPIST-1 planets may also have lower densities than SS terrestrials (Grimm et al., 2018; although an update is coming soon!).

- Both observations suggest that the TRAPPIST-1 planets may be more volatile rich than Solar System terrestrials (Luger et al., 2017; Gillon et al., 2017).
Near-term JWST observations will search for planetary atmospheres

- Multiple groups have estimated that terrestrial atmosphere detection is likely straightforward for TRAPPIST-1 with JWST.

- A high molecular-weight atmosphere may be detected in as little as 2 transits. This will largely be driven by CO$_2$ features.

- Clouds increase integration times for interior planets

---

Table 1. Number of transits or eclipses required to detect a Venus-like atmosphere

<table>
<thead>
<tr>
<th>Type of Atmosphere</th>
<th>1 bar H$_2$O</th>
<th>1 bar H$_2$O (clouds)</th>
<th>10 bar CO$_2$</th>
<th>10 bar CO$_2$ (clouds)</th>
<th>20 bar CO$_2$</th>
<th>20 bar CO$_2$ (clouds)</th>
<th>100 bar CO$_2$</th>
<th>100 bar CO$_2$ (clouds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detected</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>7</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>15</td>
<td>30</td>
<td>12</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>24</td>
<td>31</td>
<td>12</td>
<td>12</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Lustig-Yaeger et al., 2019

c.f. Wunderlich et al., 2019; Macdonald & Cowan, 2019
Possible limited characterization of planetary atmospheres

CO₂, H₂O, O₃, O₂-O₂ may be detectable in the atmosphere of TRAPPIST-1 b in relatively few transits (3-12)

To assess this planet’s evolutionary state:

1. detect a planetary atmosphere via CO₂ absorption (>2 transits)

2. detect or rule out a post-runaway oxygen-dominated atmosphere via O₂-O₂ CIA or O₃ absorption (> 12 transits)

   NB: This is an observational test of the HZ concept.

3. constrain outgassing from the interior and potential habitability via the H₂O abundance and presence of SO₂ (> 125 transits)
Detecting Earth-like Oxygen Is Unlikely with JWST

It is unlikely that we will detect biogenic O$_2$ with JWST. 0.76 $\mu$m is hopeless. 1.27 $\mu$m O$_2$ with NIRSpec G140H could be seen at SNR~1 in 30 transits, or 270 transits for SNR~3! More optimistic results for a hotter planet from Wunderlich et al., (2019) show 172 transits to S/N=5 6 $\mu$m O$_2$-O$_2$/O$_2$-N$_2$ might be promising but unlikely for TRAPPIST-1 (Fauchez et al., 2020)
Coupling high-contrast imager and high-resolution spectrographs on the VLOT and future ELTs. Planet detection and mass determination, visible O$_2$ and CH$_4$ bands.

3-$\sigma$ O$_2$ detection in 60 nights of telescope time, spread over 3 years (Lovis et al., 2016).

ELT/HIRES may take 21 transits (over 2 years) to detect O$_2$ for a planet orbiting an M4V (Rodler & Lopez-Morales, 2014). May attempt 1.27um O$_2$ for later type M dwarfs.

Most anticipated targets are within 7pc of the Earth.

But O$_2$ may be possible ground-based high-resolution spectroscopy.

---

**Figure 2.** Graphical representation of high-dispersion spectroscopic observations of carbon monoxide in the thermal spectrum of a hot Jupiter. The white curved lines indicate the planetary carbon monoxide lines, which significantly change in wavelength owing to the change in the radial component of the exoplanet orbital velocity. The dark vertical features are telluric absorption, which is stationary with time and which can therefore be filtered out.

---

Snellen et al., 2014
Things We Need: Observing Solar System Planets as Exoplanets

- Phase dependent observations inform future direct imaging missions for exoplanets
- See Laura Mayorga’s talk on Friday on phase dependent observations of the Galilean satellites.
Things We Need: Observing Solar System Planets as Exoplanets

- Occulation observations can simulate exoplanet transmission observations and help us train forward and retrieval models.
Things We Can Learn: Secondary atmospheres

- Star-planet interaction may strip an atmosphere
- May change the composition of the atmosphere
- Atmospheric loss if balanced by volatile delivery from outgassing or impactors (see Laura Schaefer’s talk this afternoon).

- Exoplaneteteers will soon need to understand these processes to predict and interpret observations of terrestrial exoplanets

- Mars and Venus could help us understand processes of atmospheric and ocean loss
Studies of Venus may inform the interpretation of highly irradiated exoterrestrials, including signs of ocean loss, and possible abiotic $\text{O}_2$ formation mechanisms.

See poster by Mike Wong.
Summary

• The solar system provides a detailed understanding of observables, processes, evolution and formation for our 8 planets and the populations of small bodies.

• Exoplanets provide a very large statistical sample that reveals the diversity of exoplanet composition, processes and evolution.

• Both communities are moving towards a systems- and process-based approach to understanding planet formation, evolution, habitability, biosignatures.
  – Requires synthesis of observations, theory and laboratory research from multiple disciplines.

• As exoplanet observations improve, we will be able to make more direct comparisons with the Solar Systems planetary systems like our own, and provide the cosmic context for our planetary system and its inhabited planets.

• An effort needs to be made to encourage the two communities to interact

One day... there will not be exoplanet scientists and Solar System scientists, there will just be planetary scientists.
SIG 3 ExoSS Synergies – Goals

- We propose to provide a forum for interaction between the Solar System and exoplanet communities on topics of mutual interest, and to work to identify ways in which NASA could enhance these interactions.

- Example activities:
  - coordination of monthly webinars with Solar System/exoplanet presenters,
  - discussion fora,
  - development of workshop proposals (e.g. Exoplanets in Our Backyard Feb 5-7, after OPAG),
  - other cross-PAG/AG activities and presentations,
  - joint SIG reports/review papers that identify beneficial avenues for future joint research between the exoplanet and Solar System communities.

- As a longer term goal, this SIG will encourage cross-disciplinary interaction between PAGs/AGs in all four NASA Divisions.

- It will report at least twice per year to the ExoPAG EC through their monthly telecons, and at least once annually at the bi-annual ExoPAG meetings.

- This SIG3 will be open to all interested community members (please contact Vikki, Stephen or Kathy if interested!)
To learn more about Solar System/exoplanet/astrobiology synergy....

Available for pre-order now: https://uapress.arizona.edu/book/planetary-astrobiology

Available in May!

....and talk to me, Dawn and Shawn about NExSS!
We may be able to identify past ocean loss

- With JWST, detecting signs of ocean loss may be easier than signs of a present ocean.
- Ocean loss can be revealed via O₂-O₂ and even HDO to attempt to determine D/H ratio.
- If we see D/H fractionation, it may indicate that an ocean is not present.
- May detect HDO in as few as 10 transits (Lincowski et al., 2019) …and see Andrew’s talk at 10:55 in Cedar.
Targets for Comparative Planetology of Terrestrial Exoplanets

- **Transiting exo-Venuses**
  - GJ1132 b (Berta-Thompson et al., 2016; Dittman et al., 2017)

- **HZ Terrestrial Planets**
  - LHS 1140 b (Dittman et al., 2016)
  - Proxima Centauri b (Anglada-Escude; non-transiting)
  - Ross 128 b (Bonfils et al., 2017; non-transiting)

- **Transiting exo-Venuses and HZ Terrestrials**
  - TRAPPIST-1 (Gillon et al., 2016; 2017; Luger et al., 2017)
  - b,c,d exo-Venuses; e,f,g, HZ planets; h beyond HZ

- **What near-term and longer term observations of exoplanet terrestrials can inform our understanding of terrestrial evolution?**

Figure Credit: NASA/JPL-Caltech
Exoplanets = Planets

Planetary evolutionary outcomes, including atmospheric composition, will be influenced by:
- planet formation and migration processes,
- interior outgassing composition and history
- history of planetary and stellar interactions -- including atmospheric loss and photochemistry

Which Solar system planetary observations and theories can illuminate key processes that affect the formation, evolution and habitability of a diversity of planets?