EXOPLANET SCIENCE STRATEGY

David Charbonneau (Co-Chair), Scott Gaudi (Co-Chair), Fabienne Bastien, Jacob Bean, Justin Crepp, Eliza Kempton, Chryssa Kouveliotou, Bruce Macintosh, Dimitri Mawet, Victoria Meadows, Ruth Murray-Clay, Evgenya Shkolnik, Ignas Snellen, Alycia Weinberger
Exoplanet Discoveries Have Increased Dramatically

Figure Credit: A. Weinberger (ESS Report)
What Do We Know Today?

(Statements from the ESS Report)

• “Planetary systems are ubiquitous and surprisingly diverse, and many bear no resemblance to the Solar System.”

• “A significant fraction of planets appear to have undergone large-scale migration from their birthsites.”

• “Most stars have planets, and small planets are abundant.”

• “Large numbers of rocky planets [have] been identified and a few habitable zone examples orbiting nearby small stars have been found.”

• “Massive young Jovians at large separations have been imaged.”

• “Molecules and clouds in the atmospheres of large exoplanets have been detected.”

• ”The identification of potential false positives and negatives for atmospheric biosignatures has improved the biosignature observing strategy and interpretation framework.”
How Did We Learn Those Lessons?

Radial Velocity
Animation by European Southern Observatory

Transit
Animation by NASA Goddard Media Studios

Astrometry
Animation by Exoplanet Exploration Office at NASA JPL

Direct Imaging
Animation by Jason Wang

Microlensing
Animation by Exoplanet Exploration Office at NASA JPL
Exoplanet Science in the 2020s & Beyond
The ESS Report Identified Two Goals

1. “Understand the formation and evolution of planetary systems as products of the process of star formation, and characterize and explain the diversity of planetary system architectures, planetary compositions, and planetary environments produced by these processes.”

2. “Learn enough about the properties of exoplanets to identify potentially habitable environments and their frequency, and connect these environments to the planetary systems in which they reside. Furthermore, researchers need to distinguish between the signatures of life and those of nonbiological processes, and search for signatures of life on worlds orbiting other stars.”
The ESS Report Identified Two Goals

1. Understand the Formation and Evolution of Planetary Systems

2. Search for Life
ESS Finding: Two Surveys are Necessary to Advance Our Understanding of Planetary Systems

1. Probe regions of **low search completeness**, including “the parameter space occupied by most planets of the Solar System”

2. Characterize “the **atmospheres and bulk compositions** of planets spanning a broad range of masses and orbits.”
WFIRST Will Dramatically Expand the Exoplanet Census

- Wide-Orbit Exoplanet Demographics (Bennet et al. 2019)
- Identification and characterization of the host stars in planetary microlensing with ELTs (Lee et al. 2019)
- Masses and Distances of Planetary Microlens Systems with High Angular Resolution Imaging (Bhattacharya et al. 2019)
- See WFIRST/Euclid talk by Jefferey Kruk (Monday morning)

Penny et al. 2018
WFIRST Will Dramatically Expand the Exoplanet Census

‘Auxiliary’ Science with the WFIRST Microlensing Survey: Measurement of the Compact Object Mass Function over Ten Orders of Magnitude; Detection of \(\sim 10^5\) Transiting Planets; Asteroseismology of \(\sim 10^6\) Bulge Giants; Detection of \(\sim 5\times 10^3\) Trans-Neptunian Objects; and Parallaxes and Proper Motions of \(\sim 6\times 10^6\) Bulge and Disk Stars (Gaudi et al. 2019)

Wide-Orbit Exoplanet Demographics (Bennet et al. 2019)

Identification and characterization of the host stars in planetary microlensing with ELTs (Lee et al. 2019)

Masses and Distances of Planetary Microlens Systems with High Angular Resolution Imaging (Bhattacharya et al. 2019)

See WFIRST/Euclid talk by Jefferey Kruk (Monday morning)
Finding: A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations greater than one AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, near-infrared (NIR), space-based mission is needed to provide a similar sample size of planets as found by Kepler.
Recommendation: NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

Finding: A space-based microlensing survey would discover thousands of planets in previously unexplored regions of parameter space.
Transiting Planets are Convenient Targets for Probing Bulk and Atmospheric Compositions
TESS Will Find Thousands of Planets

45 Earths

240 “Super-Earths”

1870 “Sub-Neptunes”

2400 giant planets

Barclay et al. (2018)
TESS planets are ideal targets for RV mass measurement

See EarthFinder talk by Peter Plavchan (Tuesday morning)
**Finding:** The radial velocity method will continue to provide essential mass, orbit, and census information to support both transiting and directly imaged exoplanet science for the foreseeable future.

**Finding:** Radial velocity measurements are currently limited by variations in the stellar photosphere, instrumental stability and calibration, and spectral contamination from telluric lines. Progress will require new instruments installed on large telescopes, substantial allocations of observing time, advanced statistical methods for data analysis informed by theoretical modeling, and collaboration between observers, instrument builders, stellar astrophysicists, heliophysicists, and statisticians.
Recommendation: NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars.

Finding: RVs are extremely useful.

Finding: Reaching sensitivity to Earth-mass planets is challenging and requires novel approaches.
Finding: High-precision, narrow-angle astrometry could play a role in the identification and mass measurement of Earth-like planets around Sun-like stars, particularly if the radial velocity technique is ultimately limited by stellar variability.
Finding: Astrometry could measure the masses of Earth-like planets orbiting G stars.

The Value of Astrometry for Exoplanet Science (Bendek et al. 2019)

Finding Exo-Earths with Precision Space Astrometry (Shao et al. 2019)
Planet Mass Estimates Inform Atmospheric Analyses

Towards Finding Earth 2.0: Masses and Orbits of Small Planets with Extreme Radial Velocity Precision (Ciardi et al. 2019)

Ground-Based Radial Velocity as Critical Support for Future NASA Earth-Finding Missions (Dressing et al. 2019)

Batalha, Kempton, & Mbarek (2017)
JWST Will Significantly Advance Our Understanding of Planetary Atmospheres

Simulated Hot Jupiter transmission spectrum & composition constraints (Bean et al. 2018)
Atmospheric Disequilibrium is a Potential Biosignature

Simulation of 10 Transits of TRAPPIST-1e Observed by JWST

Atmospheric disequilibrium as an exoplanet biosignature: Opportunities for next generation telescopes (Krissansen-Totton et al. 2019)
Atmospheric Disequilibrium is a Potential Biosignature

The Mid-Infrared Search for Biosignatures on Temperate M-Dwarf Planets (Kataria et al. 2019)

See OST Talk by Cooray (Monday morning)

From the First Stars to Life: Scientific Capabilities of the Origins Space Telescope (Cooray et al., #5023)

An Ultra-Stable Mid-Infrared Sensor for the Detection of Biosignatures by Means of Transit Spectroscopy (Staguhn et al., #5029)

Origins Space Telescope: The Mid-Infrared Transit Spectrometer Instrument (Sakon et al., #5031)

The Origins Space Telescope: Science Traceability Matrix (Meixner et al., #5034)

The Origins Space Telescope: Development of a Scientifically Compelling, Low-Risk, Executable Mission Concept (Leisawitz et al., #5015)
Finding: The combination of transiting planet detection with TESS, mass measurements with radial velocities, and atmospheric characterization with JWST will be transformative for understanding the nature and origins of close in planets. Future space missions with broader wavelength coverage, a larger collecting area, or reduced instrumental noise compared to JWST would have greater reach to potentially habitable planets.

Finding: By conducting a statistical survey of exoplanet atmospheres, the European ARIEL mission will provide broader context for more focused JWST observations. The U.S. exoplanet community would benefit from participation in ARIEL.
Recommendation: NASA should create a mechanism for community-driven legacy surveys of exoplanet atmospheres early in the JWST mission.

Finding: Atmospheric studies with JWST will dramatically transform our understanding of close-in transiting planets.

Finding: ARIEL will provide context for JWST observations.
The Exoplanet Community Has Developed a Plan to Optimize JWST Observations of Transiting Planets

Table 1: Approved GTO and ERS Transiting Planet Programs

<table>
<thead>
<tr>
<th>ID</th>
<th>Title and Science Instrument</th>
<th>Team Lead</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>1177</td>
<td>MIRI observations of transiting exoplanets</td>
<td>T. Greene</td>
<td>75</td>
</tr>
<tr>
<td>1185</td>
<td>Transit Spectroscopy of Mature Planets (NIRCam)</td>
<td>T. Greene</td>
<td>140</td>
</tr>
<tr>
<td>1201</td>
<td>NIRISS Exploration of the Atmospheric Diversity of Transiting Exoplanets</td>
<td>D. Lafrenière</td>
<td>201</td>
</tr>
<tr>
<td>1224</td>
<td>Transiting Exoplanet Characterization with JWST/NIRSPEC</td>
<td>S. Birkmann</td>
<td>50</td>
</tr>
<tr>
<td>1274</td>
<td>Extrasolar Planet Science with JWST (NIRCam)</td>
<td>J. Lunine</td>
<td>74</td>
</tr>
<tr>
<td>1279</td>
<td>Thermal emission from Trappist1-b (MIRI)</td>
<td>P.-O. Lagage</td>
<td>25</td>
</tr>
<tr>
<td>1280</td>
<td>MIRI Transiting Observation of WASP-107b</td>
<td>P.-O. Lagage</td>
<td>11</td>
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<tr>
<td>1281</td>
<td>MIRI and NIRSPEC Transit Observations of HAT-P-12 b</td>
<td>P.-O. Lagage</td>
<td>32</td>
</tr>
<tr>
<td>1312</td>
<td>Transit and Eclipse Spectroscopy of a Warm Neptune (NIRISS+NS+MIRI)</td>
<td>N. Lewis</td>
<td>36</td>
</tr>
<tr>
<td>1331</td>
<td>Transit Spectroscopy of TRAPPIST-1e (NIRSpec)</td>
<td>N. Lewis</td>
<td>22</td>
</tr>
<tr>
<td>1353</td>
<td>Transit and Eclipse Spectroscopy of a Hot Jupiter (NIRISS+NS+MIRI)</td>
<td>N. Lewis</td>
<td>72</td>
</tr>
<tr>
<td>1366</td>
<td>The Transiting Exoplanet Community ERS Program (all SIs)</td>
<td>N. Batalha</td>
<td>78</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>816</td>
</tr>
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</table>

Characterizing Transiting Exoplanets with JWST Guaranteed Time and ERS Observations (Greene et al. 2019)

Engaging Citizen Scientists to Keep Transit Times Fresh and Ensure the Efficient Use of Transiting Exoplanet Characterization Missions (Zellem et al. 2019)
The ESS Report Identified Two Goals

1. Understand the Formation and Evolution of Planetary Systems

2. Search for Life
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1. Understand the Formation and Evolution of Planetary Systems

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**Finding:** The concept of the habitable zone has provided a first-order technique for identifying exoplanets that may be able to harbor life. A multiparameter holistic approach to studying exoplanet habitability, using both theory and observation, is ultimately required for target selection for biosignature searches.

**Finding:** Inferring the presence of life on an exoplanet from remote sensing of a biosignature will require a comprehensive framework for assessing biosignatures. Such a framework would need to consider the context of the stellar and planetary environment, and include an understanding of false negatives, false positives, and their observational discriminants.
Finding: Biosignature searches require a holistic approach to habitability.

Finding: Detecting life requires a comprehensive framework for assessing biosignatures.

Life Beyond the Solar System: Remotely Detectable Biosignatures (Domagal-Goldman et al. 2019)
Habitability is Complicated

Meadows & Barnes (2018)

A Balancing Act: Biosignatures and Anti-Biosignature Studies in the Next Decade and Beyond (Harman et al. 2019)

Planetary Habitability Informed by Planet Formation and Exoplanet Demographics (Apai et al. 2019)

Characterizing Exoplanet Habitability (Robinson et al. 2019)
Stellar Characterization is a Necessary Component of the Search for Biosignatures

Finding: Understanding of exoplanets is limited by measurements of the properties of the parent stars, including stellar mass, radius, distance, binarity, rotation period, age, composition, emergent spectrum, and variability.
Stellar Characterization is a Necessary Component of the Search for Biosignatures

**Finding:** Stellar characterization is key.

- *Stellar Characterization Necessary to Define Holistic Planetary Habitability* (Hinkel et al. 2019)
- *An Interdisciplinary Perspective on Elements in Astrobiology: From Stars to Planets to Life* (Hinkel et al. 2019)
### Why Sun-like Stars?

#### The M-Dwarf Opportunity

<table>
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<tr>
<th>Potentially habitable planets orbiting M dwarfs</th>
<th>Challenges</th>
<th>Opportunities</th>
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<tbody>
<tr>
<td>Multiple barriers to habitability possible; e.g., desiccation during super-luminous pre-main sequence phase, stellar activity-driven atmospheric loss.</td>
<td>-</td>
<td>Most common type of stars (~75%).</td>
</tr>
<tr>
<td>Apparent high potential for false positive oxygen biosignatures.</td>
<td>-</td>
<td>Planets with significantly different histories to Earth valuable for comparative planetology.</td>
</tr>
<tr>
<td>Challenging to observe via direct imaging due to the small planet-star angular separation. Even nearest planets require ELTs (Crossfield 2013).</td>
<td>-</td>
<td>Transits of HZ planets more easily observed due to shorter orbital periods and deeper transit depths. May be possible with JWST and/or ELTs.</td>
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<th>Potentially habitable planets orbiting FGK dwarfs</th>
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<tr>
<td>Less common types of stars. Transit spectroscopy prohibitively difficult due to long orbital periods, small transit depths, lower transit probability. Challenging planet-star contrast ratio ($10^{-10}$ for a Sun-Earth twin in reflected light) demands starlight suppression advances.</td>
<td>-</td>
<td>Less significant barriers to habitability due to moderate stellar evolution and activity.</td>
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<td>Understand Earth in the context of planets with similar histories. Is Earth typical?</td>
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<td>Known that life can flourish on such planets. May be best opportunity for high-confidence detection of biosignatures.</td>
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**Table 1: Challenges and opportunities for HZ planets around M dwarfs and FGK dwarfs.**

**The Sun-like Stars Opportunity** (Arney et al. 2019)
Why Sun-like Stars?

The M-Dwarf Opportunity

and

the G-Dwarf Case

can be explored together!

Table 1: Challenges and opportunities for HZ planets around M dwarfs and FGK dwarfs.

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Capabilities of Current & Upcoming Direct Imagers

Figure from ESS Report. Credit: D. Mawet, B. Macintosh, T. Meshkat, V. Bailey, & D. Savransky
**Finding:** The GMT and TMT will enable profound advances in imaging and spectroscopy of entire planetary systems, over a wide range of masses, semimajor axes, and wavelengths, potentially including temperate Earth-size planets orbiting M-type stars.

**Finding:** The technology roadmap to enable the full science potential of GMT and TMT in exoplanet studies is in need of investments, leveraging the existing network of U.S. centers and laboratories and current 8-10 meter class facilities.

**Finding:** GMT and TMT, equipped with high-resolution optical and infrared spectrographs, will be powerful tools for studying the atmospheres of transiting and nontransiting close-in planets, and have the potential to detect molecular oxygen in temperate terrestrial planets transiting the closest and smallest stars.

**Finding:** The detection of young planets in disks will provide the ground truth for the time scale of planet formation and permit studies of the dynamical interaction between disks and planets. With the high spatial resolution of the GMT and TMT, researchers will be able to search the inner parts of planet-forming systems.
Finding: GMT and TMT will transform exoplanet science.

Finding: The GSMT technology roadmap requires investment.

Finding: GSMTs will probe planetary atmospheres & search for biosignatures (for M dwarf planets).

Finding: GSMTs could detect planets forming in disks.
Recommendation: The National Science Foundation (NSF) should invest in both the GMT and TMT and their exoplanet instrumentation to provide all-sky access to the U.S. Community.
Finding: A coronagraphic or starshade-based direct imaging mission is the only path currently identified to characterize Earth-size planets in the habitable zones of a large sample of nearby Sun-like stars in reflected light.

Finding: Recently acquired knowledge of the frequency of occurrence of small planets, and advances in the technologies needed to directly image them, have significantly reduced uncertainties associated with a large direct imaging mission.
**Finding:** A large direct imaging mission is required to detect Earth-like planets orbiting Sun-like stars in reflected light.

**Finding:** We have the required knowledge and technology.

**Recommendation:** NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.
A Possible Probe-Class Mission

• Small telescope
  • 1-m off-axis (e.g., CASTOR)
  • 1.5-m on-axis (e.g., CETUS probe study)
• 20-m starshade
• Observe in the UV
  • Ozone at 200 – 310 nm
  • Continuum at 310-450 nm

CASTOR: Imaging the UV/Optical Sky in the 2020s (Haggard et al., #5012)
The Cosmic Evolution Through UV Spectroscopy (CETUS) NSA Probe Mission Concept (Danchi et al., #5028)

Surveying the solar neighborhood for ozone in the UV at temperate rocky exoplanets (Lisman et al. 2019)
WFIRST-CGI + Starshade?

WFIRST/AFTA + Starshade
Simulated image

See Rendezvous Talk by Sara Seager
(Wednesday morning)

The WFIRST Coronagraphic Instrument
(Zimmerman et al., #5065)

Starshade Technology Development to TRL 5
(S5) – Technology Overview and Status
(Short et al., #5066)

See WFIRST/Euclid talk by Jefferey Kruk
(Monday morning)
Large Yields Require a Large Telescope

Optimal Architectures and Survey Designs for Maximizing the Yields of Direct-Imaging Exoplanet Missions (Stark et al. 2019)

See HabEx Talk by Gaudi & Morgan (Monday afternoon)

The Exoplanet Yield Landscape for Future Direct Imaging Telescopes (Stark et al., #5001)

See LUVOIR Talk by Fischer & Bolcar (Monday afternoon)
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The Exoplanet Yield Landscape for Future Direct Imaging Telescopes (Stark et al., #5001)

Note: The y-axis scales are different!
Studying A Diversity of Planets Is Critical

“Our recommendation for the decadal survey is that exoplanet characterization be a focus of future missions, and that these missions should be capable of studying a large number of habitable exoplanets to allow for statistically testing habitability hypotheses.”

A Statistical Comparative Planetology Approach to Maximize the Scientific Return of Future Exoplanet Characterization Efforts (Checlair et al. 2019)
UV Observations Are Essential

**Finding:** Once HST ceases operation, researchers will essentially lose the ability to gather UV spectra of exoplanet host stars, which will limit the ability to interpret spectra of the planetary atmospheres and to understand their habitability.
**Finding:** We will lose the UV when HST ends.

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The remote detectability of Earth’s biosphere through time and the importance of UV capability for characterizing habitable exoplanets (Reinhard et al. 2019)

Surveying the solar neighborhood for ozone in the UV at temperate rocky exoplanets (Lisman et al. 2019)

Understanding Exoplanet Atmospheres with UV Observations I: NUV and Blue/Optical (Christiansen et al. 2019)

Understanding Exoplanet Atmospheres with UV Observations II: the FUV and Atmospheric Escape (Lopez et al. 2019)

Transforming Ultraviolet Spectroscopy in the Next Two Decades: The LUVOIR Ultraviolet Multi-Object Spectrograph (LUMOS) (France et al., #5011)

The HabEx Ultraviolet Spectrograph (UVS) – Design and Science Drivers (Scowen, #5069)
X-Ray Observations Are Valuable For Exploring Planetary Atmospheres & Habitability

From Wolk et al. (2019). Figure by K. Poppenhaeger

X-ray Studies of Exoplanets (Wolk et al. 2019)

High-Energy Photon and Particle Effects on Exoplanet Atmospheres and Habitability (Drake et al. 2019)
Finding: The search for life outside the Solar System is a fundamentally interdisciplinary endeavor. The Nexus for Exoplanet Systems Science (NExSS) research coordination network encourages the cross-disciplinary and cross-divisional collaborations needed to support NASA exoplanet research and missions.
Finding: The search for life is an interdisciplinary endeavor.

Recommendation: Building on the NExSS model, NASA should support a cross-divisional exoplanet research coordination network that includes additional membership opportunities via dedicated proposal calls for interdisciplinary research.
**Finding:** Theoretical models are essential to plan and interpret observations of exoplanets, and are enabled by robust support via individual investigator grants.

**Finding:** Understanding of exoplanets is limited by measurements of the properties of the parent stars, including stellar mass, radius, distance, binarity, rotation period, age, composition, emergent spectrum, and variability.

**Finding:** The limited lab and ab initio data covering the parameter space relevant to exoplanets is a barrier to accurate models of exoplanet atmospheres and interiors. Mechanisms to increase collaboration between exoplanet astronomers and experimental physicists and chemists would help overcome this barrier.
**Finding:** Theoretical work is essential.

**Finding:** Lab data is limited. We should work with experimentalists.

**Finding:** We need to characterize stars.

Recommendation: NASA should support a robust individual investigator program that includes grants for theoretical, laboratory, and ground-based telescopic investigations; otherwise, the full scientific yield of exoplanet missions will not be realized.
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Finding: Theoretical work is essential.

Finding: Lab data is limited. We should work with experimentalists.

Finding: We need to characterize stars.
**Finding:** To maximize scientific potential and opportunities for excellence, institutions and organizations can enable full participation by a diverse workforce by taking concrete steps to eliminate discrimination and harassment and to proactively recruit and retain scientists from underrepresented groups.

**Finding:** Development and dissemination of concrete recommendations to improve equity and inclusion and combat discrimination and harassment would be valuable for building the creative, interdisciplinary teams needed to maximize progress in exoplanet science over the coming decades.

**Finding:** By continuing to find novel ways of partnering with each other, and by removing or reducing institutional barriers to such partnerships, agencies may be able to better address some of the most profound scientific questions outlined in this study, which often require instruments, telescopes, or missions that are too ambitious or expensive for any individual agency to fund, build, and operate alone.
**Finding:** We need to eliminate discrimination and harassment and proactively recruit and retain scientists from underrepresented groups.

**Finding:** We should develop and disseminate concrete recommendations to improve equity and inclusion and combat discrimination and harassment.

**Finding:** Partnerships enable more ambitious instruments, telescopes, and missions.

**CASTOR:** Imaging the UV/Optical Sky in the 2020s (Haggard et al., #5012)

**SPICA:** Revealing the Hearts of Galaxies and Forming Planetary Systems; Overview and US Contributions (Roelfsema & Bradford, #5051)
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Top Three Recommendations Affecting the Space Astrophysics Landscape for Exoplanet Science

NASA should lead a **large strategic direct imaging mission** capable of measuring the **reflected-light spectra** of temperate terrestrial planets orbiting **Sun-like stars**.

NASA should **launch WFIRST** to conduct its **microlensing survey** of distant planets and to demonstrate the technique of **coronagraphic spectroscopy** on exoplanet targets.

NASA should create a mechanism for **community-driven legacy surveys** of **exoplanet atmospheres** early in the **JWST mission**.
The ESS Report Has Widespread Community Support


372 Endorsers!
“Attempts to “bound the problem” or “fit in the box” drive a certain kind of thinking. The 1970s decadal is sometimes hailed as the most visionary of all decadals – as it ultimately led to Hubble. How did that happen?

That decadal committee said: here are ALL the things we would like to do. We understand the dollars are limited, but we think that all these things are SO IMPORTANT that we will write them down, and if NASA can figure out a way to do them, it should. We sometimes forget that Hubble was #9 on their list, ranked so low because the decadal committee itself did not know how NASA would afford it. But NASA found a way, and the resulting transformation of astronomy was ultimately profound.”
“In the Astro2020 decadal survey, the astrophysics community is presented with a unique opportunity. One of the most profound questions we humans ask ourselves – ‘Are we alone?’ – stands ready to be addressed in a systematic way. The scientific community can elect to survey the atmospheres of dozens of nearby exoplanets for subtle chemical imbalances or clues to surface environmental conditions that could indicate biological processes or at least potential habitability.

We just need to build a sufficiently powerful space telescope.”
Top Three Recommendations Affecting the Space Astrophysics Landscape for Exoplanet Science

NASA should lead a **large strategic direct imaging mission** capable of measuring the **reflected-light spectra** of temperate terrestrial planets orbiting **Sun-like stars**.

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NASA should create a mechanism for **community-driven legacy surveys** of **exoplanet atmospheres** early in the **JWST mission**.
Extra Slides
Combining Mass & Radius Measurements Probes Bulk Composition

![Graph showing the relationship between planet mass and radius, with categories for Terrestrials, Ice Giants, and Gas Giants, and regions for pure H₂/He, pure water, pure rock, and pure iron. The graph also highlights exoplanets and Solar System planets.](image-url)
Characterizing Exoplanet Habitability (Robinson et al. 2019)

The Sun-like Stars Opportunity (Arney et al. 2019)

Figure from Meadows (2017)
WFIRST Will Dramatically Expand the Exoplanet Census

Astro2020 White Paper (Authors)

Wide-Orbit Exoplanet Demographics (Bennet et al. 2019)

Identification and characterization of the host stars in planetary microlensing with ELTs (Lee et al. 2019)

Masses and Distances of Planetary Microlens Systems with High Angular Resolution Imaging (Bhattacharya et al. 2019)

See WFIRST/Euclid talk by Jefferey Kruk (Monday morning)
A Bayesian Framework for Life Detection

Figure from Walker et al. (2018)

\[
P(\text{life|data}) = \frac{P(\text{data|life})P(\text{life})}{P(\text{data|life})P(\text{life}) + P(\text{data|no life})(1 - P(\text{life}))}
\]

A Balancing Act: Biosignatures and Anti-Biosignature Studies in the Next Decade and Beyond (Harman et al. 2019)

Planetary Habitability Informed by Planet Formation and Exoplanet Demographics (Apai et al. 2019)

Characterizing Exoplanet Habitability (Robinson et al. 2019)

- Posterior Probability of Life
  - Detecting unknown life (see discussion on detectability)
  - Bayesian Example with $O_2$
  - Tuning search strategies
  - see also, Technology detection biases (Fujii et al. 2017, this issue)

- Likelihood of observations on non-living worlds
  - 4.1 Stellar environment
  - 4.2 Climate and Geophysics
  - 4.3 Geochemical Environment

- Likelihood of observations on living worlds
  - 5.1 Black Box Approaches to Living processes
  - 5.2 Life as Improbable Chemistry
  - 5.3 Life as an evolutionary process
  - 5.4 Insights from Universal Biology
The Distribution of Planet Radii in the Pre-Kepler Era

Data from the NASA Exoplanet Archive
The Distribution of Planet Radii in the Pre-Kepler Era

324 Planets

Data from the NASA Exoplanet Archive
The Distribution of Planet Radii in the Post-Kepler Era

3051 Planets

Data from the NASA Exoplanet Archive
Exogeoscience Spans Multiple Disciplines

Geoscience and the Search for Life Beyond the Solar System (Barnes et al. 2019)
Looking Beyond the Current Large Mission Concepts
**Finding:** Technology development support in the next decade for future characterization concepts such as mid-infrared (MIR) interferometers or very large/sparse apertures will be needed to enable strategic exoplanet missions beyond 2040.

*The Importance of Thermal Emission Spectroscopy for Understanding Terrestrial Exoplanets* (Line et al. 2019)

*The Future of Exoplanet Direct Detection* (Monnier et al. 2019)