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The Search for Life in the Universe

Fall 2015

What can we learn from Extrasolar Planets?
EXTRASOLAR HABITABILITY: EARTH-LIKE PLANETS?

A home away from home
Exoplanet Habitability

Sara Seager

The search for exoplanets includes the promise to eventually find and identify habitable worlds. The thousands of known exoplanets and planet candidates are extremely diverse in terms of their masses or sizes, orbits, and host star type. The diversity extends to new kinds of planets, which are very common yet have no solar system counterparts. Even with the requirement that a planet’s surface temperature must be compatible with liquid water (because all life on Earth requires liquid water), a new emerging view is that planets very different from Earth may have the right conditions for life. The broadened possibilities will increase the future chances of discovering an inhabited world.

Main point: the HZ (H₂O) for life may be much larger than typically estimated because the diversity of potential atmospheres (temperatures, pressures) may provide extreme greenhouse effects.
Known exoplanets as of March 2011: Exoplanets are found at a nearly continuous range of masses and semimajor axes. Many different techniques are successful at discovering exoplanets, as indicated by the different symbols. The solar system planets are denoted by the first one or two letters of their name. The horizontal line is the conventional upper limit to a planet mass, 13 Jupiter masses. The sloped, lower boundary to the collection of gray squares is due to a selection effect in the radial velocity technique. Small planets are beneath the threshold for the current state of almost all exoplanet detection techniques. Data are from http://exoplanet.eu/.
Extended Habitable Zones

- Hydrogen-atmosphere planets
- Earthlike planets
- Dry terrestrial planets

Graph shows the relationship between star type, planet type, and their habitable zones. The x-axis represents $a_{\text{exoplanet}} / a_\oplus$, while the y-axis represents $M_{\text{star}} / M_\oplus$. The graph includes symbols for different detection methods: Transit, Radial velocity, Microlensing.
The basic geometry of the Solar System—the shapes, spacings, and orientations of the planetary orbits—has long been a subject of fascination as well as inspiration for planet formation theories. For exoplanetary systems, those same properties have only recently come into focus. Here we review our current knowledge of the occurrence of planets around other stars, their orbital distances and eccentricities, the orbital spacings and mutual inclinations in multi-planet systems, the orientation of the host star’s rotation axis, and the properties of planets in binary-star systems.
Properties of a hypothetical sample of exoplanets around the nearest thousand FGK stars, based on measured planet occurrence rates.

Masses and periods, based on the Doppler results of Cumming et al. (2008) for larger planets and Mayor et al. (2011) for smaller planets.

Sizes and periods, based on the analysis of Kepler data by Fressin et al. (2013).

Many more planets to be found – in which parts of these graphs?
Multi-planet Systems

2–3 planets

rank–order of shortest period in the system

2:1 resonance with 3:2 innermost planet

4 planets

5–6 planets

KOI number

period [days]
Planet around a double-star
Circumbinary systems

- **Kepler-16**
- **Kepler-34**
- **Kepler-35**
- **Kepler-38**
- **Kepler-47**
- **PH-1**
- **Kepler-413**
- **KIC 9632895**

**Scaled orbits, $a/a_c$**

**Instability zone**
How many Earths are there?

TERRESTRIAL, HABITABLE-ZONE EXOPLANET FREQUENCY FROM KEPLER

WESLEY A. TRAUB
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; wtraub@jpl.nasa.gov

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ABSTRACT

Data from Kepler’s first 136 days of operation are analyzed to determine the distribution of exoplanets with respect to radius, period, and host-star spectral type. The analysis is extrapolated to estimate the percentage of terrestrial, habitable-zone (HZ) exoplanets. The Kepler census is assumed to be complete for bright stars (magnitude < 14.0) having transiting planets >0.5 Earth radius and periods <42 days. It is also assumed that the size distribution of planets is independent of orbital period and that there are no hidden biases in the data. Six significant statistical results are found: there is a paucity of small planet detections around faint target stars, probably an instrumental effect; the frequency of mid-size planet detections is independent of whether the host star is bright or faint; there are significantly fewer planets detected with periods <3 days, compared to longer periods, almost certainly an astrophysical effect; the frequency of all planets in the population with periods <42 days is 29%, broken down as terrestrials 9%, ice giants 18%, and gas giants 3%; the population has a planet frequency with respect to period which follows a power-law relation \( \frac{dN}{dP} \sim P^{\beta - 1} \), with \( \beta \approx 0.71 \pm 0.08 \); and an extrapolation to longer periods gives the frequency of terrestrial planets in the HZs of FGK stars as \( \eta_\oplus \approx (34 \pm 14)\% \). Thus about one-third of FGK stars are predicted to have at least one terrestrial, HZ planet.

Key words: astronomical databases: miscellaneous – planets and satellites: detection – stars: statistics

Online-only material: color figures
Basic Kepler Numbers

~ 150k stars monitored.

• 1593 planets confirmed as of June 2015.
• ~1000 planets are around F, G, and K stars.
• The sample is "complete" for orbital periods up to 42 days (1/3 of 126 days).
• < 1 % probability that a transit will be seen for any given planet (depends on sizes of star and orbit).
• Thus the total number of planets that exist is multiplied by > 100.
Figure 2. Upper: the numbers of planets in the sample are shown as a function of radius, with Poisson uncertainties. For reference, the nominal planet type is indicated for each radius range: terrestrial, ice giant, and gas giant. Lower: the ratios of numbers per bin for faint/bright host stars are shown, normalized to the totals of each. The paucity of small planets in the faint group is seen as a strong drop in this ratio in the three smallest radius bins. The slight excess of large planets around faint stars, in the three largest radius bins, is a possible indication of unrecognized false-positive detections.

Figure 3. Upper: the numbers of planets detected in each period bin in the sample are shown, with Poisson uncertainties. For reference, the nominal period ranges are indicated: for $P < 3$ days, the sample is complete, so the apparent drop-off is astrophysical in origin; for $3 \, \text{days} < P < 42$ days, the sample is also complete; for $P > 42$ days, the sample is not complete, and may be biased, so the drop-off is likely an artifact. Lower: the ratios of numbers for faint/bright host stars are shown, normalized to an average of unity. Within the completely sampled range ($P < 42$ days), there does not appear to be any bias from faint targets compared to bright ones. However the apparently systematic trend toward a relatively smaller number of long-period planets around faint targets, compared to bright ones, is a possible bias at the $1\sigma$ level.
Figure 4. Period and radius of *Kepler* planets in the sample, around bright stars, are plotted. The lower right corner is relatively empty, probably owing to low S/N there, not because small planets are absent from long periods. The upper left corner is relatively sparse, in spite of an expected high S/N there, implying a deficit of large planets on short-period orbits. The left side of the diagram is relatively empty owing to an apparent paucity of planets of all sizes at periods less than 3 days. The right side of the diagram is not completely sampled in the current database, so should be ignored here.
Figure 5. Distribution of planets in the population is shown as a function of period. The distribution is based on a projection from bright stars in the sample database, using the probability of transit as a projection factor for each planet. The data are from Table 4. In the 3–42 day range, the bins are fit by a power law $dN/d\ln P \sim P^\beta$ with $\beta = 0.71 \pm 0.08$ (thick line), and extrapolated to longer periods (upper dashed line, labeled “a”). The habitable zone ranges for FGK stars are indicated. The integrated number of planets in these ranges, multiplied by the fraction of terrestrial planets, gives the estimated value of $\eta_B$. The lower dashed line, labeled “b,” is a fit to the data with periods >42 days, however these data are not complete, so the projection is not expected to be a true representation of the distribution in the population.
Orbital periods for planets inside the HZs for F,G,K stars

Three different HZs defined, wide → narrow

### Table 7
Habitable-zone Periods

<table>
<thead>
<tr>
<th>HZ Type</th>
<th>Characteristic</th>
<th>(a_\odot) Range (AU)</th>
<th>(P(F)) Range (days)</th>
<th>(P(G)) Range (days)</th>
<th>(P(K)) Range (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Wide</td>
<td>0.72–2.00</td>
<td>297–1377</td>
<td>267–1238</td>
<td>228–1057</td>
</tr>
<tr>
<td>Case 2</td>
<td>Nominal</td>
<td>0.80–1.80</td>
<td>348–1176</td>
<td>313–1057</td>
<td>267–903</td>
</tr>
<tr>
<td>Case 3</td>
<td>Narrow</td>
<td>0.95–1.67</td>
<td>451–1050</td>
<td>405–944</td>
<td>346–807</td>
</tr>
</tbody>
</table>

**Notes.** Columns 1 and 2 list the case number and one-word description of the three types of HZ in this paper, Column 3 gives the Sun–planet separation range for each Case, and Columns 4–6 give the corresponding period ranges for FGK stars.
Fraction of Earth-like Planets, 
Eta-Earth $\eta_\oplus$

$$\eta_\oplus = \frac{\text{Number of planets that are Earth-like in HZ around solar-like stars}}{\text{Total number of stars surveyed}}$$

- “Earth-like” means:
  - Radius between $\frac{1}{2}$ and 2 times Earth’s radius.
  - In the HZ defined by (possible) existence of liquid H$_2$O.

- “Solar-like” means:
  - F, G, and K type stars (0.7 to 1.7 M$_\odot$).
  - The HZs of F, G, K stars correspond to orbital periods that are > the completeness period of the Kepler survey.
    - Estimation of eta-Earth requires extrapolation of the current planet statistics to longer orbital periods.
  - A “reasonable” extrapolation gives

- ~One Earth-like planet for every three solar-like star in the Kepler sample.
- Solar system: $\sim 2$.

$$\eta_\oplus \approx 0.34 \pm 0.14$$
Prevalence of Earth-size planets orbiting Sun-like stars

Erik A. Petigura\textsuperscript{a,b,1}, Andrew W. Howard\textsuperscript{b}, and Geoffrey W. Marcy\textsuperscript{a}

\textsuperscript{a}Astronomy Department, University of California, Berkeley, CA 94720; and \textsuperscript{b}Institute for Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822

Determining whether Earth-like planets are common or rare looms as a touchstone in the question of life in the universe. We searched for Earth-size planets that cross in front of their host stars by examining the brightness measurements of 42,000 stars from National Aeronautics and Space Administration's \textit{Kepler} mission. We found 603 planets, including 10 that are Earth size ($1-2 \ R_\oplus$) and receive comparable levels of stellar energy to that of Earth ($0.25-4 \ F_\oplus$). We account for \textit{Kepler}'s imperfect detectability of such planets by injecting synthetic planet-caused dimmings into the \textit{Kepler} brightness measurements and recording the fraction detected. We find that 11 \pm 4\% of Sun-like stars harbor an Earth-size planet receiving between one and four times the stellar intensity as Earth. We also find that the occurrence of Earth-size planets is constant with increasing orbital period ($P$), within equal intervals of \log$P$ up to \sim 200 d. Extrapolating, one finds $5.7^{+1.7}_{-2.2}$ \% of Sun-like stars harbor an Earth-size planet with orbital periods of 200–400 d.

A major question is whether planets suitable for biochemistry are common or rare in the universe. Small rocky planets with liquid water enjoy key ingredients for biology.

\begin{itemize}
  \item \textbf{Kepler:} 42,000 stars surveyed; 603 planets, 10 of which are Earth size and orbit in the habitable zone, where conditions permit surface liquid water.
  \item Measured the detectability of these planets by injecting synthetic planet-caused dimmings into \textit{Kepler} brightness measurements.
  \item 26 \pm 3\% of Sun-like stars have an Earth-size planet with $P = 5$–100 d.
  \item 11 \pm 4\% of Sun-like stars harbor an Earth-size planet that receives nearly Earth levels of stellar energy
\end{itemize}

The nearest such planet may be within 12 light-years.
2D domain of orbital period and planet size, on a logarithmic scale.

Petigura E A et al. PNAS 2013;110:19273-19278
Planet occurrence as a function of orbital period and planet radius for $P = 6.25 - 400$ d and $R_P = 0.5$ to 16 Earth radii.
The measured distributions of planet sizes (A) and orbital periods (B) for and $P = 5$–$100$ d.

Petigura E A et al. PNAS 2013;110:19273-19278
The detected planets (dots) in a 2D domain similar to Figs. 1 and 2.

\[ F_P = 0.25 - 4 \, F_\oplus \]
\[ R_P = 1 - 2 \, R_\oplus \]
The fraction of stars having nearly Earth-size planets with any orbital period up to a maximum period, $P$, on the horizontal axis.

$5.7^{+2.2}_{-1.7}$% of Sun-like stars have a planet with $P=200-400$ d, $R_P = 1-2R_E$

Petigura E A et al. PNAS 2013;110:19273-19278
Prevalence of Earth-size planets orbiting Sun-like stars

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doi: 10.1073/pnas.1319909110

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The nearest such planet may be within 12 light-years.
Ultimately, a return to study of compelling individual objects is required—at any cost—if we want to assess a planet’s habitability or attain the goal of identifying signs of life via biosignature gases. Is there any hope that the next space telescope, the James Webb Space Telescope, could be the first to provide evidence of biosignature gases? Yes, if—and only if—every single factor is in our favor. First, we need to discover a pool of super-Earths transiting in the “extended” habitable zones of nearby, quiet M stars. Second, life must not only exist on one of those planets, but must also produce biosignature gases that are spectroscopically active. Regardless of the search for life, the field of exoplanet characterization is on track to understand habitability and to find habitable worlds.
What’s the weather like?

STUDYING EXTRASOLAR PLANETS
The future of spectroscopic life detection on exoplanets

Sara Seager¹

Department of Physics and Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139

Edited by Adam S. Burrows, Princeton University, Princeton, NJ, and accepted by the Editorial Board June 26, 2014 (received for review December 16, 2013)

The discovery and characterization of exoplanets have the potential to offer the world one of the most impactful findings ever in the history of astronomy—the identification of life beyond Earth. Life can be inferred by the presence of atmospheric biosignature gases—gases produced by life that can accumulate to detectable levels in an exoplanet atmosphere. Detection will be made by remote sensing by sophisticated space telescopes. The conviction that biosignature gases will actually be detected in the future is moderated by lessons learned from the dozens of exoplanet atmospheres studied in last decade, namely the difficulty in robustly identifying molecules, the possible interference of clouds, and the permanent limitations from a spectrum of spatially unresolved and globally mixed gases without direct surface observations. The vision for the path to assess the presence of life beyond Earth is being established.
<table>
<thead>
<tr>
<th>Temperature comparisons</th>
<th>Venus</th>
<th>Earth</th>
<th>Kepler 22b</th>
<th>Mars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Equilibrium Temperature</td>
<td>307 K 34 °C 93 °F</td>
<td>255 K −18 °C −0.4 °F</td>
<td>262 K −11 °C 22.2 °F</td>
<td>206 K −67 °C −88.6 °F</td>
</tr>
<tr>
<td>+ Venus' GHG effect</td>
<td>737 K 464 °C 867 °F</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Earth's GHG effect</td>
<td>288 K 15 °C 59 °F</td>
<td>295 K 22 °C 71.6 °F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Mars' GHG effect</td>
<td></td>
<td></td>
<td>210 K −63 °C −81 °F</td>
<td></td>
</tr>
<tr>
<td>Tidally locked[17]</td>
<td>Almost</td>
<td>No</td>
<td>Unknown</td>
<td>No</td>
</tr>
<tr>
<td>Global Bond Albedo</td>
<td>0.9</td>
<td>0.29</td>
<td>Unknown</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Refs.[18][19][20]
Earth as an exoplanet, via observed disk-integrated spectra. (A) Visible-wavelength spectrum from Earthshine measurements plotted as normalized reflectance. (B) Near-infrared spectrum from NASA’s EPOXI mission with flux in units of W m\(^{-2}\) µm\(^{-1}\). (C) Mid-infrared spectrum as observed by Mars Global Surveyor enroute to Mars with flux in units of W m\(^{-2}\) Hz\(^{-1}\). Major molecular absorption features are noted, including Rayleigh scattering. Only Earth’s spectroscopically active, globally mixed gases would be observable from a remote space telescope.

Extrasolar Planet Observation and Deep Impact Extended Investigation = EPOXI
Biomarkers: Signs of Life

Spectral lines in the atmospheres of exoplanets may signify the presence of life. E.g., oxygen lines.
Exoplanet Spectroscopy

See thermal radiation from planet disappear and reappear

Measure size of transiting planet, see radiation from star transmitted through the planet’s atmosphere

Gravitational tug of unseen planets alters transit times

“Light and shadow from distant worlds”
Drake Deming & Sara Seager
Nature 462, 301-306 (19 November 2009)
Transit Spectroscopy

When HD 209458b passes in front of the star, some starlight must pass through its atmosphere.

Charbonneau et al. detected excess sodium absorption during transit, showing that HD 209458b has sodium in its atmosphere.
Differential Spectroscopy

Take a spectrum of HD 189733 in and out of eclipse (not transit).

**Differential spectroscopy**: The difference between the two is the spectrum of HD 189733b.

Grillmair et al. (2007): **No water** (based on data at 8 mm). But differential spectroscopy is very difficult. The difference spectrum is only 0.1% of the total, even in the infrared.
“Strong water absorption in the dayside emission spectrum of the planet HD189733b”

Grillmair et al.
Nature 456, 767-769 (December 2008)
Exoplanet Spectroscopy

The measured spectrum (black triangles), and two theoretical spectra of the predominantly H₂ atmosphere, showing the effects of small amounts of water (blue) and methane in combination with water (orange).

“The presence of methane in the atmosphere of an extrasolar planet”
Swain et al. Nature 452, 329-331 (Feb 2008)

(HD189733b)
Exoplanet Spectroscopy

Measurements of HD 189733b from Charbonneau et al. (2008), and HD 209458b from Knutson et al. (2008b), compared to a standard model (HD 189733b) and a temperature-inverted model (HD 209458b) from Burrows et al. (2008).

Still at the edge of technical capabilities. New telescopes and spacecraft missions being planned.
Exoplanet Spectral Modeling

HD 189733b transmission spectrum data with data points from HST STIS, ACS, WFC3, NICMOS, and Spitzer. The gray line shows a synthetic spectrum with a dust-free model. The dotted lines, from left to right, indicate the effect of Rayleigh scattering at 2,000 and 1,300 K, a cloud with grain sizes increasing linearly with pressure, and an opaque cloud deck.
Mapping Exoplanet Atmospheres


- Hot Jupiters are tidally locked (like the Moon around Earth).
- As the planet approaches eclipse, we see more and more of its hot side, facing the star.
- By tracking its infrared emission during the orbit, we can map the surface.
- The emission peaks before the eclipse!
Mapping Exoplanet Atmospheres


- The hot spot is not directly underneath the substellar point.
- High winds must be present.

We are not just detecting exoplanets now, we’re studying their weather!
# Exoplanet Characterization

<table>
<thead>
<tr>
<th>Orbital Phase</th>
<th>Science Enabled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transit (primary eclipse)</td>
<td>Radius measurement</td>
</tr>
<tr>
<td></td>
<td>Mass measurements (when combined with radial velocity)</td>
</tr>
<tr>
<td></td>
<td>Bulk composition inferred from mass &amp; radius</td>
</tr>
<tr>
<td></td>
<td>Atmospheric absorption spectroscopy</td>
</tr>
<tr>
<td></td>
<td>Detection of unseen planets via timing variations</td>
</tr>
<tr>
<td></td>
<td>Measurement of the relative inclination of stellar spin angular momentum versus</td>
</tr>
<tr>
<td></td>
<td>planetary orbital angular momentum, via the Rossiter-McLaughlin effect</td>
</tr>
<tr>
<td>Secondary eclipse</td>
<td>Measurement of the emergent spectrum of the planet</td>
</tr>
<tr>
<td></td>
<td>Measurement of orbit eccentricity (or limits thereon)</td>
</tr>
<tr>
<td></td>
<td>Ultra-high spatial resolution, mapping the disk of the planet (in longitude,</td>
</tr>
<tr>
<td></td>
<td>expected to be achieved by JWST)</td>
</tr>
<tr>
<td>Other orbit phases</td>
<td>Longitudinal temperature maps and inferences concerning zonal winds</td>
</tr>
<tr>
<td></td>
<td>Spectroscopy of the planet at all longitudinal aspects (in principle, but not</td>
</tr>
<tr>
<td></td>
<td>yet achieved)</td>
</tr>
</tbody>
</table>
A small nearby star with an Earth-like planet

Berta-Thompson et al.,
Nature, 12 Nov 2015
A small nearby star with an Earth-like planet

Zachory K. Berta-Thompson et al.,
Nature, 12 Nov 2015:
“A rocky planet transiting a nearby low-mass star”

- Discovery of GJ 1132b, only 12 parsecs away from our Sun.
- Gliese 1132 is considerably smaller than our Sun, which will facilitate studies of the exoplanet’s atmosphere.
- Planet density consistent with an Earth-like bulk composition.
- 19 times more stellar radiation than the Earth: planet is too hot to be habitable but is cool enough to support a substantial atmosphere, one that has probably been considerably depleted of hydrogen.
Exoplanet masses and compositions
Earth lost most of its H, He because its atmosphere was too hot.
The amount of nebular gas accumulated and retained depends strongly on planet mass, nebula temperature, opacity assumptions and accretion timescale. An Earth-like body eliminating its energy of formation in a million years and with only pressure-induced opacity of hydrogen develops an atmosphere with $M_{\text{atm}}/M \approx 0.01$, where $M$ is planet mass and $M_{\text{atm}}$ is atmospheric mass. More opaque models yield atmospheric masses with $M_{\text{atm}}/M \approx 0.001$, in agreement with detailed models.

The retention of a major part of this atmosphere is difficult at Earth orbit once most of the nebula has cleared, but becomes increasingly likely at greater distances, especially once the atmosphere has cooled (so that the photosphere is no longer large compared with the solid body). The atmospheric escape time can be as short as a million years at one astronomical unit early in the Solar System, but longer than the age of the Solar System in the interstellar medium. Sputtering (collision with interstellar molecular or atomic hydrogen at tens to hundreds of kilometres per second) can be important if denser interstellar regions are encountered, but the column density of hydrogen in the case of $M_{\text{atm}}/M \approx 0.001$ to 0.01 is so large that removing such an atmosphere would correspond to much more mass being sputtered per unit area than the total mass per unit area of a comet in the Oort cloud.

The melting point of water is typically exceeded for basal pressures of the order of one kilobar. The atmosphere will have several cloud layers (methane, ammonia and perhaps water, like Uranus), but this has little influence on the temperature estimate.

It seems, then, that bodies with water oceans are possible in interstellar space. The ideal conditions are plausibly at an Earth mass or slightly less, similar to the expected masses of embryos ejected during the formation of giant planets. Bodies with Earth-like water reservoirs may have an ocean underlain with a rock core. Either way, these bodies are expected to have volcanism in the rocky component and a dynamo-generated magnetic field leading to a well developed (very large) magnetosphere. Despite thermal radiation at microwave frequencies that corresponds to the temperatures deep within their atmospheres (analogous to Uranus), and despite the possibility of non-thermal radio emission, they will be very difficult to detect.

If life can develop and be sustained without sunlight (but with other energy sources, plausibly volcanism or lightning in this instance), these bodies may provide a long-lived, stable environment for life (albeit one where the temperatures slowly decline on a billion-year timescale). The complexity and biomass may be low because the energy source will be small, but it is conceivable that these are the most common sites of life in the Universe.

Details of the above results are available from the author.
Are free floating planets common?

... we detect significant variability in the young, free-floating planetary mass object PSO J318.5-22, likely due to rotational modulation of inhomogeneous cloud cover.
Are free floating planets common?

… we detect significant variability in the young, free-floating planetary mass object PSO J318.5-22, likely due to rotational modulation of inhomogeneous cloud cover. (Biller et al. 2015)

“Molten metal storms rage on orphan planet that lost its star.”

New Scientist, 2 November 2015
The future of spectroscopic life detection on exoplanets

Sara Seager
Department of Physics and Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139

The discovery and characterization of exoplanets have the potential to offer the world one of the most impactful findings ever in the history of astronomy—the identification of life beyond Earth. Life can be inferred by the presence of atmospheric biosignature gases—gases produced by life that can accumulate to detectable levels in an exoplanet atmosphere. Detection will be made by remote sensing by sophisticated space telescopes. The conviction that biosignature gases will actually be detected in the future is moderated by lessons learned from the dozens of exoplanet atmospheres studied in last decade, namely the difficulty in robustly identifying molecules, the possible interference of clouds, and the permanent limitations from a spectrum of spatially unresolved and globally mixed gases without direct surface observations. The vision for the path to assess the presence of life beyond Earth is being established.

• Near future: Transiting planet discovery and characterization with Transiting Exoplanet Survey Satellite and JWST.
• Intermediate future: Small space telescopes for direct imaging.
• Far future: Large space-based telescope to search 1,000 Sun-like stars.
• Beware of systematics, ambiguous signatures, and false positives.
A schematic diagram of a representative starshade (also called an external occulter) flying in formation with a telescope (represented on the far right) to provide starlight suppression and enable imaging of a companion exoplanet at a small geometric inner working angle. Because of diffraction, the starshade must be tens of meters in diameter and fly tens of thousands of km from the telescope.