

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.

astrobiology | spectroscopy

For thousands of years, people have wondered, “Are we alone?”. Astronomers have now ascertained, statistically speaking, that every star in our Milky Way Galaxy should have at least one planet (1) and that small rocky planets are extremely common (2, 3). Our own Galaxy has 100 billion stars, and our Universe has upwards of 100 billion galaxies—making the chance for life elsewhere seem inevitable based on sheer probability. We can say with certainty that, for the first time in human history, we are finally on the verge of being able to search for signs of life beyond our solar system around the nearest hundreds of stars.

Over one-half a century ago, people realized that signs of life could be recognized on a distant planet by remote sensing of gases in the planet atmosphere (4, 5). A key assumption is that life uses chemistry for storage and use of energy and that some metabolic products will be in gaseous form. We call gases that are produced by life that can accumulate in a planet atmosphere to detectable levels biosignature gases. Exoplanets by their sheer number can offer a large quantity of worlds to explore for signs of life, which is in contrast to solar system bodies where in situ observations are possible, but the number of planetary bodies with the right conditions for life is limited.

In the last two decades, astronomers have succeeded in developing a variety of methods (6) to discover and characterize exoplanets. Among these methods are techniques to study exoplanet atmospheres. To date, spectra have been measured for a handful of exoplanet atmospheres and broadband

spectrophotometry has been used for dozens more, although mostly limited to hot planets orbiting close to their host stars (7, 8).

Today, there have been enough observational and theoretical studies of exoplanet atmospheres to glimpse both prospects and limitations of the future. Of specific interest is what kind of atmospheric characterization is likely achievable for small rocky planets. Lessons learned from current exoplanet atmosphere studies are critical for any future approach to search for atmospheric biosignature gases.

In the coming decade or two, we will have a lucky handful of potentially habitable exoplanets with atmospheres that can be observed in detail with the next generation of sophisticated space telescopes. These telescopes include the planned James Webb Space Telescope (JWST) (9). Also possible is a small space-based direct imaging telescope that is under study by National Aeronautics and Space Administration (NASA) (10, 11) but not yet planned to go forward. There will be such a small number of potentially habitable planets accessible for observations that, to not miss our chance to infer the presence of life beyond Earth, we must embrace the reality of exoplanet diversity. We must keep an open mind regarding which planets could be habitable and which atmospheric gases might be potential signs of life.

In the distant future, we must construct and launch a very large space telescope (well exceeding 10 m in diameter) (12) to find over 100 potentially habitable exoplanets to assess their atmospheres for biosignature gases or the likelihood thereof. Only with a large pool

of Earth-like planets may we gain a probabilistic assessment of the commonality of biosignature gases by mitigating the inevitability of false positives. In other words, although we may not be able to point to a planet with certainty and say, “that planet has signs of life,” with enough rocky worlds with biosignature gases, we will inspire confidence that life not only exists in the solar neighborhood but is common in our Galaxy.

Implications of the Diversity of Exoplanets

In the past 20 y of exoplanet discovery, one of the most significant findings is the sheer diversity of exoplanets. Solar system analogs must be somewhat rare; although they are relatively challenging to detect, none are yet known. It seems that less than 10–20% of Sun-like stars could host solar system copies. Instead, astronomers have found that exoplanets and exoplanetary systems are incredibly varied, with planets of nearly all conceivable masses and sizes as well as orbital separations from their host star (13). One of the most surprising exoplanet findings is that the most common type of planet is not a Jupiter-sized planet but a planet about two times the size of Earth or smaller (3). Other highlights of exoplanet diversity include a preponderance of sub-Neptune-sized

Author contributions: S.S. reviewed and analyzed existing material and wrote the paper.

The author declares no conflict of interest.

This article is a PNAS Direct Submission. A.S.B. is a guest editor invited by the Editorial Board.

¹Email: seager@mit.edu.

planets (14, 15) that are between Earth and Neptune sizes with no solar system counterpart and formation that is not yet understood (e.g., ref. 16); circumbinary planets (17); compact multiple planet systems (18), including at least one with five planets orbiting interior to what would be Mercury's orbit (19); and hot rocky worlds that are expected to have surfaces heated by their star to over 2,000 K, which is hot enough to create liquid lava surfaces [Kepler 10b (20) and Kepler 78b (21, 22)].

The diversity of exoplanet masses, sizes, and orbits illustrates the stochastic nature of planet formation, and we expect this diversity to extend to exoplanet atmospheres in terms of both atmospheric mass and composition. The atmospheric mass and composition of any specific exoplanet are not predictable (23), and in addition, observations are not yet able to measure atmospheric composition or yield estimates of atmospheric mass. It is nonetheless worth summarizing some key factors controlling a planet atmosphere. A planet's atmosphere forms from outgassing during planet formation or is gravitationally captured from the surrounding protoplanetary nebula. The amount of gas captured or outgassed is not known and may vary widely. For terrestrial planets, the primordial atmosphere may be completely changed by escape of light gases to space, continuous outgassing from an active young

interior, and bombardment by asteroids and comets. At a later stage, the physical processes operating at the top or bottom of the atmosphere still sculpt the atmosphere, including thermal and nonthermal atmospheric escape of light gases, volcanism, and plate tectonics. A review of Earth's atmospheric evolution is in ref. 24.

The diversity of exoplanets, both observed and theorized, motivates a revised view of exoplanet habitability (25) (Fig. 1). A habitable planet is generally defined as one that requires surface liquid water, because all life on Earth requires liquid water. Surface liquid water, in turn, requires a suitable surface temperature. Because the climates (and hence, surface temperature) of planets with thin atmospheres are dominated by external energy input from the host star, a star's habitable zone (26, 27) is based on distance from the host star. Small stars, with their relatively low luminosity outputs, have a habitable zone much closer to them compared with Sun-like stars. In addition to the energy from the host star, it is the greenhouse warming effects of rocky planet atmospheres that control the surface temperature. The revised view is that planet habitability is planet-specific, because the huge range of planet diversity in terms of masses, orbits, and star types should extend to planet atmospheres based on the stochastic

nature of planet formation and subsequent evolution.

The habitable zone for solar type stars has been described to range from about 0.5 (for dry planets) (refs. 28 and 29 but cf. ref. 30) to 10 AU [for predominantly rocky planets with hydrogen atmospheres (31) orbiting a Sun-like star or even beyond, depending on the planet interior and atmosphere characteristics (32)]. The extension of the habitable zone is somewhat controversial, because at the small planet–star separation end, there is limited understanding of planetary processes, such as volcanism, plate tectonics, and hydration rates, on low-water reservoir exoplanets. At the larger planet–star separation end, there is an inability to determine which of the many thermal and nonthermal atmospheric escape processes are dominant on planets with unknown compositions and host star UV radiation history.

Extreme caution should be taken with the quantitative predictability of exoplanet habitable zone models based on the complicated physics and the imposed model input conditions (including but not limited to planet obliquity and planet atmosphere mass). In particular and as a good example, there is serious disagreement in the literature about the inner edge of the habitable zone. For example, information in ref. 28, which finds an inner edge of 0.5 AU, differs substantially from information in ref. 29, which finds an inner edge of 0.77 AU. Although ref. 28 used a 1D model and ref. 29 used a 3D model, the most significant difference is likely the relative humidity (28), because a 1D model must impose a globally averaged relative humidity (1% imposed by ref. 28), whereas a general circulation model (GCM) can calculate the relative humidity (which appears closer to 10% in ref. 29). The 1% value originates from an order of magnitude estimate based on very dry equatorial regions and moist poles that will have liquid precipitation, a case that should apply for very dry planets that have reasonably fast rotation rates. This basic postulate is being further investigated with the MIT 3D GCM. One possible reconciliation between refs. 28 and 29 is that a 3D model could yield a much lower global relative humidity with an increased range of parameter space, such as that investigated in ref. 28 (including surface gravity, surface albedo, and stellar type). Ultimately, observations of a rocky planet with water vapor at a small planet–star separation will be needed to try and settle this debate.

Regardless of model-based opinion, we must keep an open mind in the choice of exoplanets to search for signs of life simply to increase the chances of success.

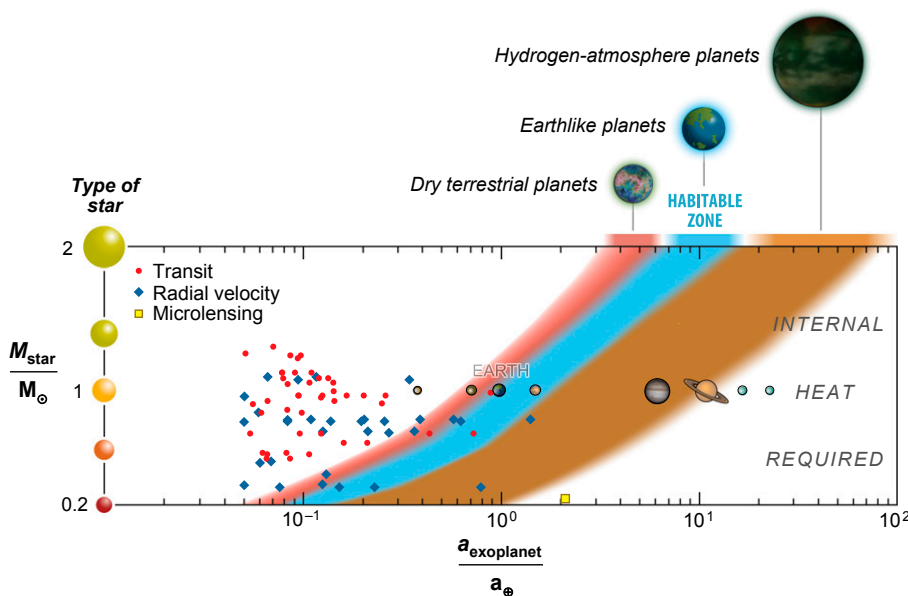


Fig. 1. The extended habitable zone. The blue region depicts the conventional habitable zone for N_2 - CO_2 - H_2O atmospheres (27, 30). The dark pink region shows the habitable zone as extended inward for dry planets (28, 29) as dry as 1% atmospheric relative humidity (28). The outer orange brown region shows the outer extension of the habitable zone for hydrogen-rich atmospheres (31), and it can even extend out to free-floating planets with no host star (32). The solar system planets are shown with images. Known super Earths (planets with a mass or minimum mass less than 10 Earth masses taken from ref. 86). Modified from ref. 25.

Lessons Learned from Exoplanet Atmospheres Studies

In the last two decades, astronomers have observed over three dozen exoplanet atmospheres. The first atmosphere measurement was atomic sodium in the atmosphere of HD 209458b (33). At the time, one would have described the prediction (34) as straightforward: a ball of gas of assumed solar composition heated by the star and controlled by chemical equilibrium tells us the dominant atmospheric gases. The tremendous progress made over the past two decades by way of observation of dozens of exoplanet atmospheres, as well as related theory and interpretation, has, in some ways, raised more questions than answers.

The bulk of atmosphere observations to date has been accomplished by the transit method, where transiting planets are those that go in front of their star as seen from the telescope. When the planet is in front of the star, some of the starlight passes through the planet atmosphere, picking up atmospheric spectroscopic features. When the planet disappears behind the star and reappears, secondary eclipse spectroscopy enables a wavelength-dependent brightness determination of the planet (8).

Four transiting exoplanet atmospheres have been observed in detail by transmission spectroscopy and help to highlight the lessons learned from exoplanet atmospheres [HD 209458b (35), HD 189733 (36, 37), GJ 436b (38), and GJ 1214b (39)].

The first lesson learned is that exoplanet atmospheres are diverse; however, this statement is based on a small number of statistics. The first two exoplanets listed above are hot Jupiter planets, and their atmospheres have major differences. HD 209458b shows no signs of clouds, and the cooler HD 189733b does show signs of hazes and clouds.

The second lesson learned is that hazes and clouds (40) can be a dominating factor in transmission spectroscopy. This finding has been surprising, because the hot planets (with atmospheric temperatures ranging from several hundred to well over 1,000 K) were initially thought to have atmospheres at too high of temperatures for solid particles to condense for haze or cloud formation. The exoplanet HD 189733b spectrum is shown in Fig. 2, with data points throughout the visible and near-IR wavelengths strongly suggesting the presence of both haze (based on the slope of the short-wavelength spectrum) and clouds (based on the featureless spectrum at longer wavelengths). The exoplanet GJ 1214b (41) is another excellent case in point. Initially bringing great excitement for transmission spectroscopy prospects (42), progress required substantial amounts of the Hubble Space Telescope time to bin data from 15 transits [using Wide Field Camera 3 (WCF3) at 1.1–1.7 μm ; this wavelength range encompasses absorption by H_2O , CH_4 , and CO_2]. The resulting spectrum is featureless, which may mean that clouds have masked any molecular absorption by blocking out much of the atmosphere below them (39).

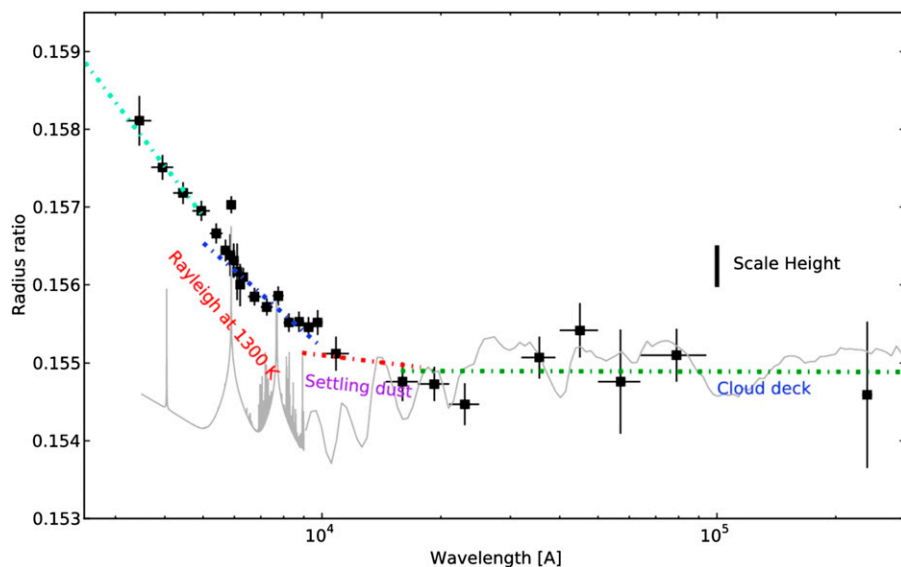


Fig. 2. HD 189733b transmission spectrum data with data points from HST Space Telescope Imaging Spectrograph, Advanced Camera for Surveys, WFC3, NICMOS, and Spitzer Space Telescope. The gray line shows a synthetic spectrum with a dust-free model. The dotted lines, from left to right, indicate the effect of Rayleigh scattering at 2,000 and 1,300 K, a cloud with grain sizes increasing linearly with pressure, and an opaque cloud deck. Modified from ref. 36.

The Neptune mass exoplanet GJ 436b (38) also shows a featureless transmission spectrum—with the same instrument and wavelength range as GJ 1214b—possibly with the same cloudy atmosphere interpretation. As an added note, the secondary eclipse in reflected light of Kepler 7b shows highly reflective clouds (43).

The third lesson learned falls into the instrument-related category: that medium-resolution spectroscopy is required over sparse spectrophotometry, high signal-to-noise ratio (SNR) data are required, and if systematics are too serious, the dataset should be ignored. The identification of molecules based on four to six spectrophotometry points is questionable (7), although logically argued if the number of unknown molecules is less than the number of data points (44). Compelling results based on several photometric data points, such as planets with high C/O ratios in their atmospheres (45, 46), are not assured. The only clearly robust detections of molecules are with higher spectral resolution, such as, for example, the high-dispersion ground-based spectroscopy cross-correlation method (47) and new Hubble Space Telescope WFC3 spatial scan observations (35, 48, 49). High SNR is required. It, for example (50), showed that not just 1 but up to 10 transits with data binned together were required to study the planet GJ 1214b given its initial apparent lack of spectral features. Instrument systematics with Hubble Space Telescope (HST) Near Infrared Camera and Multi-Object Spectrometer (NICMOS) detectors (possibly owing to temperature variations during the day/night cycle of low Earth orbit) may be responsible for the controversy of the strength of water vapor on HD 189733b (51, 52).

Lessons learned should all be applied to future instrumentation and space missions for smaller planets—to the extent possible, test detectors in the laboratory for systematics and expect the unexpected with regards to planet atmosphere composition. The goal is to prepare for a future of remote sensing of signs of life by way of atmospheric gases that can be attributed to life.

Biosignature Gases

The starting point for the search for life on exoplanets by remote sensing of atmospheric gases begins with Earth, the only planet with life, and indeed, the concept has been exhaustively studied (53–62). A conservative extension of a planet with a very Earth-like atmosphere around star types other than the Sun is ongoing (63–66). The biosignature gas research included in these references has focused, to date, on the dominant

biosignature gases found on Earth, O_2 (and its photochemical product O_3) and N_2O , as well as the possibility of CH_4 on early Earth. Research forays into biosignature gases that are negligible on present day Earth but may play a significant role on other planets began with Pilcher (67), who suggested that organosulfur compounds, particularly methanethiol (CH_3SH , the sulfur analog of methanol), could be produced in high enough abundance by bacteria, possibly creating a biosignature on other planets. CH_3Cl was first considered in ref. 67, and sulfur biogenic gases on anoxic planets were comprehensively investigated in ref. 68.

Life, indeed, produces a vast array of gases (69). In fact, one must recognize that life produces many of the gases in Earth's atmosphere (specifically the troposphere) present at the parts-per-trillion level by volume or higher—with the exception of the noble gases. Most of Earth's atmospheric gases are, of course, not unique to

life. Some are already naturally occurring (e.g., N_2 , CO_2 , and H_2O). Many are produced geologically (e.g., CH_4 and H_2S). What is the best approach to life detection by biosignature gases if, in general, so many gases might be produced by life?

Over one-half a century ago, the approach to remote detection of signs of life on another planet was set out in refs. 4 and 5, which introduced the canonical concept for the search for an atmosphere with gases severely out of thermochemical redox equilibrium. Redox chemistry adds or removes electrons from an atom or molecule (reduction or oxidation, respectively). Redox chemistry is used by all life on Earth and thought to enable more flexibility than nonredox chemistry (70). The idea that gas byproducts from metabolic redox reactions can accumulate in the atmosphere was initially favored for future biosignature identification, because abiotic processes were thought to be less likely to create a redox disequilibrium. There are now

concrete contradictory examples based on simulations regarding abiotic generation of CO (71, 72). Regarding Earth's atmosphere, both oxygen (a highly oxidized species) and methane (a very reduced species) are several orders of magnitude out of thermochemical redox equilibrium. In practice, it could be difficult to detect both molecular features of a redox disequilibrium pair. The Earth as an exoplanet, for example (Fig. 3), has a relatively prominent oxygen absorption feature at $0.76\ \mu m$, whereas methane (at present day levels of 1.6 ppm) has only extremely weak spectral features. During early Earth, CH_4 may have been present at much higher levels (1,000 ppm or even 1%), because it was possibly produced by widespread methanogen bacteria (73). Such high CH_4 concentrations would be easier to detect, but because the Earth was not oxygenated during early times, the O_2 - CH_4 redox pairs would be challenging to detect concurrently (ref. 54 and cf. ref. 74), unless perhaps for a planet in a lower-UV radiation environment (possible with some M star hosts) (63).

The Lederberg-Lovelock approach could be useful at the time when hundreds or thousands of rocky exoplanets have observed atmospheres—to increase the chance that two spectroscopically active gases that are redox opposites might simultaneously exist in the lifetime evolution of a planet. In the shorter term, a different approach is needed to optimize our chances to detect biosignature gases, if they exist, around a handful of accessible potentially habitable worlds. (Note that subsurface life is problematic for astronomical techniques because remote sensing may not be able to detect weak signs of life by biosignature gases coming from the interior.)

An idealized atmospheric biosignature gas approach is to detect a single spectroscopically active gas completely out of chemical equilibrium with the atmosphere that is many orders of magnitude higher than expected from atmospheric photochemical equilibrium. False positives will, in many cases, be a problem, and in the end, we will have to develop a framework for assigning a probability to a given planet to have signs of life.

To understand biosignature gases, it is useful to divide them into two broad categories. The first category (called Type I in ref. 75) is gases that are byproduct gases produced from metabolic reactions that capture energy from environmental redox chemical potential energy gradients. Such gases (such as CH_4 from methanogenesis) are likely to be abundant but always fraught with false positives. They are abundant, because they are

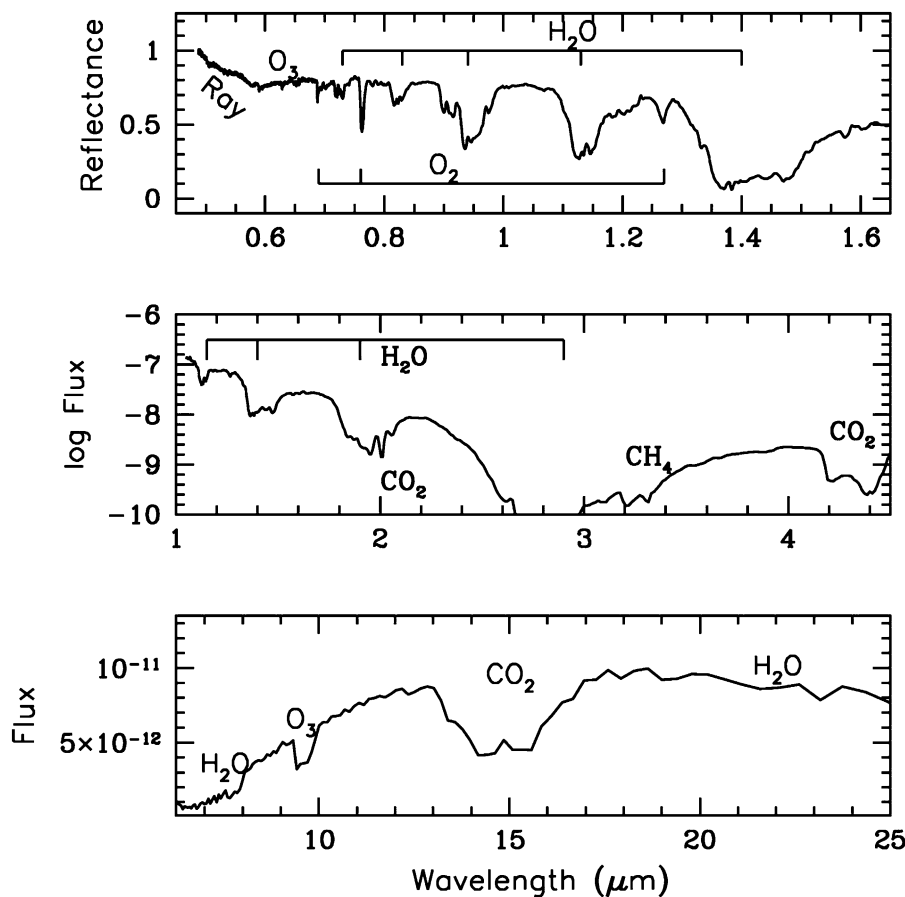


Fig. 3. Earth as an exoplanet spectrum through an observed disk-integrated spectrum. (Top) Visible wavelength spectrum from Earthshine measurements plotted as normalized reflectance (60). (Middle) Near-IR spectrum from NASA's Extrasolar Planet Observation and Deep Impact Extended Investigation mission, with flux in units of watts meter⁻² micrometer⁻¹ (87). (Bottom) Mid-IR spectrum as observed by Mars Global Surveyor en route to Mars, with flux in units of Watts meter⁻² Hertz⁻¹ (88). 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.

created from chemicals that are plentiful in the environment. They are fraught with false positives, because geology has the same molecules to work with as life; also, in one environment, a given redox reaction will be kinetically inhibited and thus, proceed only when activated by life's enzymes, and in another environment with the right conditions (temperature, pressure, concentration, and acidity), the same reaction might proceed spontaneously.

A second category of biosignature gases (called Type III in ref. 75) is chemicals produced by life for reasons other than energy capture or the construction of the basic components of life; they are generally expected to be produced in smaller quantities but will have a wider variety and much lower possibility of false positives compared with Type I biosignature gases. These qualities are seen, because Type III biosignature gases are produced for organism-specific reasons and they are highly specialized chemicals not directly tied to the local chemical environment and thermodynamics. Type III gases include DMS, methanethiol, some other sulfur gases (68, 69), methyl chloride (63), and isoprene (69). Note that Type II refers to biomass-building biosignature gases, such as CO₂, which are not unique enough to be useful.

Low UV radiation environments, such as on planets with low-UV active M dwarf stars, are favorable. For Sun–Earth-like UV radiation environments, OH is created when H₂O and/or CO₂ are photodissociated, and OH is a powerful radical that destroys many gases in a planet atmosphere (60). In Sun–Earth-like UV radiation environments, planets with H₂-rich atmospheres, atomic H, produced from H₂ photodissociation (and in some cases, O, which is produced from CO₂), is the destructive molecule and will rapidly destroy nearly all biosignature gases of interest (76). A low-UV environment means that biosignature gases will be less likely to be destroyed than in a high-UV radiation environment, enabling biosignature gases to be more likely to accumulate to significant levels in the exoplanet atmosphere.

In summary, many different gases are produced by life, but the anticipated diversity of exoplanet atmosphere composition and host star environments may yield different detectable biosignature gases than the terrestrial examples. Even with excellent data, false positives will drive a permanent ambiguity in many cases. If a planet has a biosignature gas that is hard to produce abiologically in large quantities (such as DMS), we can identify it as a biosignature gas if we can also analyze the rest of the

atmosphere for environmental context (e.g., false positives).

Prospects for Exoplanet Life Detection.

To astronomically detect biosignature gases, we must remotely observe atmospheres using sophisticated, next-generation telescopes. In general, to find small planets bright enough for atmosphere characterization, including the search for biosignature gases, we must find planets orbiting stars that are nearby to our own Sun. Although NASA's Kepler Space Telescope (77) has found a multitude of small planets, they are distant enough to make the planets and their atmospheres too faint to study.

Near future: Transiting planet discovery and characterization with Transiting Exoplanet Survey Satellite and JWST. The near-term plan (for the next decade) is established. The plan is to search for Earth-sized and larger rocky planets transiting small stars. This approach is sometimes called a fast track over the search for the true Earth analog (an Earth-like planet in an Earth-like orbit about a Sun-like star). The motivation for the fast track is that the discovery of an Earth analog is an enormous challenge, because Earth is so much smaller ($\sim 1/100$ in radius), so much less massive ($\sim 1/10^6$), and so much fainter ($\sim 10^7$ for mid-IR wavelengths to $\sim 10^{10}$ for visible wavelengths) than the Sun. A super Earth transiting a small, low-luminosity M star (and in the M star's habitable zone) is so much more favorable for detection an Earth–Sun analog in a number of ways (78).

An important consideration is that the discovered rocky exoplanets be bright enough for atmosphere characterization, including the search for biosignature gases. Bright means nearby, and therefore, the near-term plan is to find planets orbiting stars that are close to our own Sun. Although NASA's Kepler Space Telescope has provided a critical census of exoplanets and found a multitude of small exoplanets, they are too distant for near-future follow-up studies of their atmospheres.

NASA's Transiting Exoplanet Survey Satellite (TESS) mission (79), scheduled for launch in 2017, will survey nearby stars for transiting exoplanets. Transiting exoplanets are those that pass in front of their parent star as seen from the telescope, a phenomena that is exploited as a planet discovery technique that NASA's Kepler mission (as well as many other telescopes) has used to discover more than 3,500 potential exoplanets. TESS is an NASA Explorer-class mission (\$230 million cost cap exclusive of launch costs) led by the Massachusetts Institute of Technology. TESS will carry four identical specialized

wide-field CCD cameras, each covering $24^\circ \times 24^\circ$ on the sky with a 100-mm aperture. In a 2-y all-sky survey of the solar neighborhood, TESS will cover 400 times as much sky as Kepler did. In the process, TESS will examine more than 0.5 million bright nearby stars and likely find thousands of exoplanets with orbital periods (i.e., years) up to about 50 d. TESS will not be able to detect true Earth analogs (that is, Earth-sized exoplanets in 365-d orbits about Sun-like stars), but it will be capable of finding Earth-sized and super Earth-sized exoplanets (up to 1.75 times Earth's size) transiting M stars, stars that are significantly smaller, cooler, and more common than our Sun. TESS is projected to find hundreds of super Earths, with a handful of those in an M star's habitable zone. Extensive follow-up observations by worldwide ground-based observatories will then be used to measure the planet mass to confirm the exoplanets as being rocky.

NASA's JWST (9), scheduled to launch in 2018, will be capable of studying the atmospheres of a subset of the TESS rocky exoplanets in visible, near-IR, and IR radiation. The technique that JWST will use is called transit spectroscopy. As a transiting exoplanet passes in front of its host star, we can observe the exoplanet's atmosphere as it is backlit by the star. Additional atmospheric observations can be made by watching as the exoplanet disappears and reappears from behind the star. In these observations, the exoplanets and their stars are not spatially separated on the sky but instead, observed in the combined light of the planet–star system. We anticipate that TESS will find dozens of super Earths suitable for atmosphere observations by JWST, including several super Earths that could potentially be habitable. Life detection with the TESS–JWST combination—albeit small—is a possibility if life turns out to be ubiquitous in exoplanetary systems.

Intermediate future: Small space telescopes for direct imaging. The exoplanet discovery and atmospheric characterization techniques of TESS–JWST are powerful but very limited to the rare set of exoplanets that are fortuitously aligned to transit their host stars. A different kind of exoplanet finding and characterization technique is required to increase the chances of finding an exoplanet with habitable conditions and signs of life. Simply put, we need to take pictures of potentially habitable exoplanets. Astronomers call this direct imaging. To maximize our chances for finding life beyond the Solar System, we must develop the capability to directly

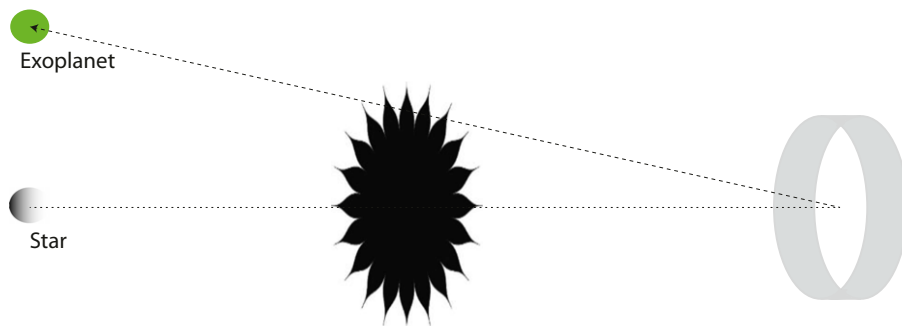


Fig. 4. A schematic diagram of a representative starshade (middle of figure; also called an external occulter) flying in formation with a telescope (represented on the far right) to provide starlight suppression and enable imaging of a companion exoplanet at a small geometric inner working angle. The orange source is a star, and the blue source is a planetary companion. Because of diffraction, the starshade must be tens of meters in diameter and fly tens of thousands of kilometers from the telescope. Modified from ref. 85.

image exoplanets around as many nearby stars as possible.

Any Earth-like exoplanets within dozens of light years are about as faint as the faintest galaxies ever observed by the Hubble Space Telescope, but first, to detect biosignatures, we have to divide the light into individual wavelengths to detect spectra; hence, we will ultimately need telescopes larger than the Hubble. Second, even more challenging is that these exoplanets are adjacent to a parent star that is up to 10 billion times brighter than the planet itself. The challenge of direct imaging of an Earth analog is similar to the search for a firefly in the glare of a searchlight when the firefly and searchlight are 2,500 miles distant (the separation from the east coast to the west coast of the United States). Direct imaging to find and characterize small exoplanets requires space telescopes above the blurring effect of Earth's atmosphere.

Two different direct imaging techniques are currently under development that, in the future, could enable direct imaging of Earth analogs. One technique is the internal coronagraph, where specialized optics are placed inside a space telescope to block out the parent starlight and reveal the presence of any orbiting exoplanets (80–82). The telescope must be highly specialized, with an observatory system that has exceptional thermal and mechanical stability. Tiny telescope imperfections that scatter starlight can be canceled out using a small mirror with thousands of adjustable elements. The corrections are equivalent to the telescope mirror being smoothed to subnanometer levels, a dimension many thousands of times smaller than the width of a human hair. Such control has already been shown in a laboratory vacuum test setup at the instrument subsystem level. A variety of different coronagraph architectures are under development

as well as deformable mirrors for ultra-precise wavefront control. NASA is investigating the addition of an internal coronagraph instrument to the Astrophysics Focused Telescope Asset; Wide-Field Infrared Survey Telescope mission, and although such an instrument would not reach down to observe small exoplanets, it would be able to study atmospheres of giant exoplanets.

The second technique under development for direct imaging of Earths is a starshade and telescope system (83, 84) (Fig. 4). A starshade (also called an external occulter) is a spacecraft with a carefully shaped screen flown in formation with a telescope. The starshade size and shape and the starshade-telescope separation are designed so that the starshade casts a very dark and highly controlled equivalent of a shadow, where the light from the star is suppressed while leaving the planet's reflected light unaffected; only the exoplanet light enters the telescope. Most designs feature a starshade tens of meters in diameter and separated from the telescope by tens of thousands of kilometers. The starshade and telescope system may be the best near-term step for discovering and characterizing nearby Earth analogs; because the starlight blocking is done by the starshade outside of the telescope itself, the telescope system throughput can be made very high, and a relatively simple and small commercially available space telescope can be used. Starshade technology development draws on industrial heritage of large space-based deployable radio antennas. So far, technology milestones include subscale vacuum chamber and environmental demonstrations, precision manufacturing of starshade petal edges, and starshade occulter stowage and deployment. Current laboratory-based experiments have shown dark shadows within about an

order of magnitude of what is required in space (85).

Recent mission concept studies show that either the internal coronagraph or the starshade direct imaging techniques with small telescopes (on order of 1- to 2-m class) is capable of observing nearby Sun-like stars to both detect exoplanets and spectroscopically characterize their atmospheres (10, 11). Such small telescope aperture missions, if appropriately designed, have the capability of finding an Earth-like exoplanet if they are prevalent.

Far future: Large space-based telescope to search 1,000 Sun-like stars. To venture beyond the lucky possibility of detecting an Earth and be realistic about assessing the probability for life under the multitude of false positives, we need larger numbers of Earth-like planet candidates and not just one or two crudely measured planet atmospheres to argue over.

To be confident of finding a large enough pool of exoplanets to search for biosignature gases, we require the ability to directly image exoplanets orbiting 1,000 or more of the nearest Sun-like stars. The concept is that only with a large pool of Earth-like planets may we gain a probabilistic confidence of the existence of biosignature gases by mitigating the inevitability of false positives. Surveying a large number of stars will require a next-generation space telescope beyond JWST (an optical-wavelength telescope with a large diameter likely exceeding 10 m) (12). Studies are ongoing within the astronomy community to outline the mission concept and technology investment required.

Closing

We stand on a great threshold in the human history of space exploration. On the one side of this threshold, we know with certainty that planets orbiting stars other than the Sun exist and are common. NASA's Kepler Space Telescope has found that approximately one in five Sun-like stars should host an Earth-sized exoplanet in the star's habitable zone (3). On the other side of this great threshold is the robust identification of Earth-like exoplanets with habitable conditions and signs of life inferred by the detection of biosignature gases in exoplanetary atmospheres. If life is prevalent in our neighborhood of the Galaxy, it is within our reach to be the first generation in human history to finally cross this threshold and learn if there is life of any kind beyond Earth.

ACKNOWLEDGMENTS. I thank Charles Darrow, Drake Deming, Julien de Wit, and Andras Zsom for interesting questions and/or useful discussion.

- 1 Cassan A, et al. (2012) One or more bound planets per Milky Way star from microlensing observations. *Nature* 481(7380):167–169.
- 2 Fressin F, et al. (2013) The false positive rate of Kepler and the occurrence of planets. *Astrophys J* 766:81–100.
- 3 Marcy GW, Weiss LM, Petigura EA, Isaacson H, Howard AW, Buchhave LA (May 27, 2014) Occurrence and core-envelope structure of 1–4x Earth-size planets around Sun-like stars. *Proc Natl Acad Sci USA* 111:12655–12660.
- 4 Lederberg J (1965) Signs of life. Criterion-system of exobiology. *Nature* 207(992):9–13.
- 5 Lovelock JE (1965) A physical basis for life detection experiments. *Nature* 207(997):568–570.
- 6 Seager S (2011) *Exoplanets*, ed Seager S (Univ of Arizona Press, Tucson, AZ).
- 7 Seager S, Deming D (2010) Exoplanet atmospheres. *Annu Rev Astron Astrophys* 48:631–672.
- 8 Burrows AS (January 13, 2014) Spectra as windows into exoplanet atmospheres. *Proc Natl Acad Sci USA* 111:12601–12609.
- 9 Gardner JP, et al. (2006) The James Webb Space Telescope. *Space Sci Rev* 123:485–606.
- 10 Science and Technology Definition Team and the Exo-S Design Team (2014) *Exo-S: Starshade Probe-Class Exoplanet Direct Imaging Mission Concept Interim Report*. Available at http://exep.jpl.nasa.gov/stdt/Exo-S_InterimReport.pdf. Accessed July 28, 2014.
- 11 Science and Technology Definition Team and the Exo-C Design Team (2014) *Exo-C Imaging Nearby Worlds. Exoplanet Direct Imaging: Coronagraph Probe Mission Study Interim Report*. Available at http://exep.jpl.nasa.gov/stdt/Exo-C_InterimReport.pdf. Accessed July 28, 2014.
- 12 Postman M, et al. (2009) Advanced Technology Large-Aperture Space Telescope (ATLAST): A technology roadmap for the next decade. arXiv:0904.0941.
- 13 exoplanet TEAM (1995) *Extrasolar Planets Encyclopaedia*. Available at <http://exoplanet.eu/catalog/>. Accessed July 28, 2014.
- 14 Howard AW (2013) Observed properties of extrasolar planets. *Science* 340(6132):572–576.
- 15 Sumi T, et al. (2010) A cold Neptune-mass planet OGLE-2007-BLG-368Lb: Cold neptunes are common. *Astrophys J* 710:1641–1653.
- 16 Chiang E, Laughlin G (2013) The minimum-mass extrasolar nebula: In situ formation of close-in super-Earths. *Mon Not R Astron Soc* 431:3444–3455.
- 17 Doyle LR, et al. (2011) Kepler-16: A transiting circumbinary planet. *Science* 333(6049):1602–1606.
- 18 Lissauer JJ, et al. (2011) Architecture and dynamics of Kepler's candidate multiple transiting planet systems. *Astrophys J* 197(Suppl): 8–33.
- 19 Lissauer JJ, et al. (2011) A closely packed system of low-mass, low-density planets transiting Kepler-11. *Nature* 470(7332):53–58.
- 20 Batalha NM, et al. (2011) Kepler's First Rocky Planet: Kepler-10b. *Astrophys J* 729:27–47.
- 21 Howard AW, et al. (2013) A rocky composition for an Earth-sized exoplanet. *Nature* 503(7476):381–384.
- 22 Pepe F, et al. (2013) An Earth-sized planet with an Earth-like density. *Nature* 503(7476):377–380.
- 23 Elkins-Tanton LT, Seager S (2008) Ranges of atmospheric mass and composition of super-Earth exoplanets. *Astrophys J* 685:1237–1246.
- 24 Kasting JF, Catling D (2003) Evolution of a habitable planet. *Annu Rev Astron Astrophys* 41:429–463.
- 25 Seager S (2013) Exoplanet habitability. *Science* 340(6132): 577–581.
- 26 Hart MH (1979) Habitable zones about main sequence stars. *Icarus* 37:351–357.
- 27 Kasting JF, Whitmire DP, Reynolds RT (1993) Habitable zones around main sequence stars. *Icarus* 101(1):108–128.
- 28 Zsom A, Seager S, de Wit J, Stamenkovic V (2013) Toward the minimum inner edge distance of the habitable zone. *Astrophys J* 778:109–125.
- 29 Abe Y, Abe-Ouchi A, Sleep NH, Zahnle KJ (2011) Habitable zone limits for dry planets. *Astrobiology* 11(5):443–460.
- 30 Kasting JF, Kopparapu R, Ramirez RM, Harman CE (November 25, 2013) Remote life-detection criteria, habitable zone boundaries, and the frequency of Earth-like planets around M and late K stars. *Proc Natl Acad Sci USA* 111:12641–12646.
- 31 Pierrehumbert R, Gaidos E (2011) Hydrogen greenhouse planets beyond the habitable zone. *Astrophys J* 734:L13–L17.
- 32 Stevenson DJ (1999) Life-sustaining planets in interstellar space? *Nature* 400(6739):32.
- 33 Charbonneau D, Brown TM, Noyes RW, Gilliland RL (2002) Detection of an extrasolar planet atmosphere. *Astrophys J* 568:377–384.
- 34 Seager S, Sasselov DD (2000) Theoretical transmission spectra during extrasolar giant planet transits. *Astrophys J* 537:916–921.
- 35 Deming D, et al. (2013) Infrared transmission spectroscopy of the exoplanets HD 209458b and XO-1b using the Wide Field Camera-3 on the Hubble Space Telescope. *Astrophys J* 774:95–111.
- 36 Pont F, et al. (2013) The prevalence of dust on the exoplanet HD 189733b from Hubble and Spitzer observations. *Mon Not R Astron Soc* 432:2917–2944.
- 37 Evans TM, et al. (2013) The deep blue color of HD 189733b: Albedo measurements with Hubble Space Telescope/Space Telescope Imaging Spectrograph at visible wavelengths. *Astrophys J* 772:L16–L20.
- 38 Knutson HA, Benneke B, Deming D, Homeier D (2014) A featureless transmission spectrum for the Neptune-mass exoplanet GJ436b. *Nature* 505:66–68.
- 39 Kreidberg L, et al. (2014) Clouds in the atmosphere of the super-Earth exoplanet GJ1214b. *Nature* 505:69–72.
- 40 Marley M, et al. (2013) Clouds and hazes in exoplanet atmospheres. arXiv:1301.5627.
- 41 Charbonneau D, et al. (2009) A super-Earth transiting a nearby low-mass star. *Nature* 462(7275):891–894.
- 42 Bean JL, Kempton EM, Homeier D (2010) A ground-based transmission spectrum of the super-Earth exoplanet GJ 1214b. *Nature* 468(7324):669–672.
- 43 Demory B-O, et al. (2013) Inference of inhomogeneous clouds in an exoplanet atmosphere. *Astrophys J* 776:25–31.
- 44 Madhusudhan N, Seager S (2010) On the inference of thermal inversions in hot Jupiter atmospheres. *Astrophys J* 725:261–274.
- 45 Kuchner MJ, Seager S (2005) Extrasolar carbon planets. arXiv: astro-ph/0504214.
- 46 Madhusudhan N, et al. (2011) A high C/O ratio and weak thermal inversion in the atmosphere of exoplanet WASP-12b. *Nature* 469(7328):64–67.
- 47 Snellen IAG, de Kok RJ, de Mooij EJV, Albrecht S (2010) The orbital motion, absolute mass and high-altitude winds of exoplanet HD 209458b. *Nature* 465(7301):1049–1051.
- 48 Wakeford, et al. (2013) HST hot Jupiter transmission spectral survey: Detection of water in HAT-P-1b from WFC3 near-IR spatial scan observations. *Mon Not R Astron Soc* 435:3481–3493.
- 49 Swain MR, Deroo P, Wagstaff KL (2013) Comparing the WFC3 IR grism stare and spatial-scan observations for exoplanet characterization. arXiv:1311.3934.
- 50 Benneke B, Seager S (2013) How to distinguish between cloudy mini-Neptunes and water/volatile-dominated super-Earths. *Astrophys J* 778:153–171.
- 51 Swain MR, Vasisht G, Tinetti G (2008) The presence of methane in the atmosphere of an extrasolar planet. *Nature* 452(7185): 329–331.
- 52 Gibson NP, Pont F, Aigrain S (2011) A new look at NICMOS transmission spectroscopy of HD 189733, GJ-436 and XO-1: No conclusive evidence for molecular features. *Mon Not R Astron Soc* 411:2199–2213.
- 53 Leger A, et al. (1996) Could we search for primitive life on extrasolar planets in the near future? *Icarus* 123:249–255.
- 54 Des Marais DJ, et al. (2002) Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. *Astrobiology* 2(2):153–181.
- 55 Selsis F, Despois D, Pariset J-P (2002) Signature of life on exoplanets: Can Darwin produce false positive detections. *Astron Astrophys* 388:985–1003.
- 56 Segura A, et al. (2003) Ozone concentrations and ultraviolet fluxes on Earth-like planets around other stars. *Astrobiology* 3(4): 689–708.
- 57 Tinetti G, et al. (2006) Detectability of planetary characteristics in disk-averaged spectra II: Synthetic spectra and light-curves of earth. *Astrobiology* 6(6):881–900.
- 58 Kaltenegger L, Traub WA, Jucks KW (2007) Spectral evolution of an Earth-like planet. *Astrophys J* 658:598–616.
- 59 Ford EB, Seager S, Turner EL (2001) Characterization of extrasolar terrestrial planets from diurnal photometric variability. *Nature* 412(6850):885–887.
- 60 Turnbull M, et al. (2006) Spectrum of a habitable world: Earthshine in the near-infrared. *Astrophys J* 644:551–559.
- 61 Pallé E, Osorio MR, Barrena R, Montañés-Rodríguez P, Martín EL (2009) Earth's transmission spectrum from lunar eclipse observations. *Nature* 459(7248):814–816.
- 62 Stam DM (2008) Spectropolarimetric signatures of Earth-like extrasolar planets. *Astron Astrophys* 482:989–1007.
- 63 Segura A, et al. (2005) Biosignatures from Earth-like planets around M dwarfs. *Astrobiology* 5(6):706–725.
- 64 Kaltenegger L, Segura A, Mohanty S (2011) Model spectra of the first potentially habitable super-Earth—GJ581d. *Astrophys J* 733:35–46.
- 65 Rauer H, et al. (2011) Potential biosignatures in super-Earth atmospheres. I. Spectral appearance of super-Earths around M dwarfs. *Astron Astrophys* 529:8–21.
- 66 Hedelt P, et al. (2013) Spectral features of Earth-like planets and their detectability at different orbital distances around F, G, and K-type stars. *Astron Astrophys* 553:9–22.
- 67 Pilcher CB (2003) Biosignatures of early earths. *Astrobiology* 3(3): 471–486.
- 68 Domagal-Goldman SD, Meadows VS, Claire MW, Kasting JF (2011) Using biogenic sulfur gases as remotely detectable biosignatures on anoxic planets. *Astrobiology* 11(5):419–441.
- 69 Seager S, Schrenk M, Bains W (2012) An astrophysical view of Earth-based metabolic biosignature gases. *Astrobiology* 12(1): 61–82.
- 70 Bains W, Seager S (2012) A combinatorial approach to biochemical space: Description and application to the redox distribution of metabolism. *Astrobiology* 12(3):271–281.
- 71 Kasting JF (1992) Bolide impacts and the oxidation state of carbon in the Earth's early atmosphere. *Orig Life Evol Biosph* 20:199–231.
- 72 Zahnle K, Haberle RM, Catling DC, Kasting JF (2008) Photochemical instability of the ancient Martian atmosphere. *J Geophys Res* 113(E11):E11004.
- 73 Haqq-Misra JD, Domagal-Goldman SD, Kasting PJ, Kasting JF (2008) A revised, hazy methane greenhouse for the Archean Earth. *Astrobiology* 8(6):1127–1137.
- 74 Pavlov AA, Hurlgen MT, Kasting JF, Arthur MA (2003) Methane-rich Proterozoic atmosphere? *Geology* 31:87–90.
- 75 Seager S, Bains W, Hu R (2013) A biomass-based model to estimate the plausibility of exoplanet biosignature gases. *Astrophys J* 775:104.
- 76 Seager S, Bains W, Hu R (2013) Biosignature gases in H₂-dominated atmospheres on rocky exoplanets. *Astrophys J* 777:95–113.
- 77 Borucki WJ, et al. (2010) Kepler planet-detection mission: Introduction and first results. *Science* 327(5968):977–980.
- 78 Nutzman P, Charbonneau D (2008) Design considerations for a ground-based transit search for habitable planets orbiting M Dwarfs. *Publ Astron Soc Pac* 120:317.
- 79 Ricker GR, et al. (2014) The Transiting Exoplanet Survey Satellite. arXiv:1406.0151.
- 80 Science and Technology Definition Team (2006) *Terrestrial Planet Finder Coronagraph*. Jet Propulsion Laboratory Document D-34923. Available at http://exep.jpl.nasa.gov/files/exep/STDT_Report_Final_Ex2FF86A.pdf. Accessed December 16, 2013.
- 81 Guyon O, Pluzhnik EA, Kuchner MJ, Collins B, Ridgway ST (2006) Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs. *Astrophys J* 167(Suppl):81–99.
- 82 Trauger J, et al. (2010) ACCESS: A concept study for the direct imaging and spectroscopy of exoplanetary systems. *Proc SPIE* 7731:773128–773140.
- 83 Cash W (2006) Detection of Earth-like planets around nearby stars using a petal-shaped occulter. *Nature* 442(7098):51–53.
- 84 Savransky D, et al. (2010) Occulting ozone observatory science overview. *Proc SPIE* 7731:77312H.
- 85 Kasdin NJ, et al. (2013) Recent progress on external occulter technology for imaging exosolar planets. *Proceedings of the Aerospace Conference, 2013 IEEE*, 10.1109/AERO.2013.6497155.
- 86 Rein H (2012) A proposal for community driven and decentralized astronomical databases and the Open Exoplanet Catalogue. arXiv:1211.7121.
- 87 Robinson TD, et al. (2011) Earth as an extrasolar planet: Earth model validation using EPOXI earth observations. *Astrobiology* 11(5): 393–408.
- 88 Christensen PR, Pearl JC (1997) Initial data from the Mars Global Surveyor thermal emission spectrometer experiment: Observations of the Earth. *J Geophys Res* 102:10875–10880.