REVIEW

The search for signs of life on exoplanets at the interface of chemistry and planetary science

Sara Seager[1,2]* and William Bains[1,3]

The discovery of thousands of exoplanets in the last two decades that are so different from planets in our own solar system challenges many areas of traditional planetary science. However, ideas for how to detect signs of life in this mélange of planetary possibilities have lagged, and only in the last few years has modeling how signs of life might appear on genuinely alien worlds begun in earnest. Recent results have shown that the exciting frontier for biosignature gas ideas is not in the study of biology itself, which is inevitably rooted in Earth's geochemical and evolutionary specifics, but in the interface of chemistry and planetary physics.

INTRODUCTION

Our Milky Way Galaxy is teeming with exoplanets—statistically speaking at least one for each of the hundreds of billions of stars in the galaxy (1). Thousands of planets have been discovered, with thousands of more planet candidates identified (2). Several different planet-finding techniques have matured and contribute to our present knowledge of exoplanets (3). Each technique has different sensitivities that favor a planet-star separation and planet mass or size range limits (Fig. 1). Because of the selection effect, none of the current exoplanet-finding techniques can find solar system copies. Astronomers have nonetheless found a completely unexpected diversity of exoplanets, a veritable "zoo" containing many astonishing planet types.

The discovery of exoplanets so different from planets in our own solar system is driving the fields of planetary formation, evolution, structure, and orbital mechanics in new directions. Planet formation models (4) are challenged by the sheer diversity of exoplanet masses, sizes, and orbits (Fig. 1), which speak to the stochastic nature of planet formation. A specific, astonishing finding is that the most common type of planet in our galaxy are those with sizes between those of Earth and Neptune—a new class of planet that is neither terrestrial nor giant and one without an accepted theory for its formation (5, 6).

Hundreds of planets are known to orbit many times closer to their star than Mercury is to our sun, with some heated to greater than 1000 K. The planets may have formed much further from the star where material in the protoplanetary disc surrounding a nascent star was plentiful enough. The planets would have then migrated inward to their current location where we infer from extrapolated observations of star formation there is not enough material to form planets. Many fundamental aspects of planet migration are still being worked out (4).

At the opposite extreme of planets close to their star are giant planets that orbit far outside of what would be considered the outer solar system, up to dozens of times farther from their star than Pluto's separation from our Sun. These planets must have formed in a massive disc that had plenty of material at large distances from the forming star (7, 8), discs that must be much more massive and extensive than our own solar nebula was.

Planets on orbits between the hot planets and the cold planets are also known (Fig. 1), and of particular interest is the "habitable zone"

(9), the zone around a star where a rocky planet with a thin atmosphere, heated by its star, may have liquid water on its surface. So far, a number of small, presumably rocky, planets in the habitable zone are known, mostly from the Kepler space telescope [recently reviewed in (10), including Earth-sized planets (11, 12)].

We would like to know which planets are habitable, that is, which planets actually have clement surface temperatures. So far, exoplanet sizes and/or masses, and orbits are measured. There is as yet no telescope capability to study atmospheres of small rocky planets in their stars' habitable zones. Atmospheres are expected to widely vary in the greenhouse properties (atmospheric mass and composition) that control the surface temperature, as a natural extension of the diversity of exoplanet masses, densities, and orbits. The anticipated diversity of greenhouse effects suggests that we might have to revise our estimates of where inner and outer habitable zone edge boundaries are in relation to the host star (13), although more conservative habitable zone boundaries are the norm for the moment (14).

We cannot send space probes across interstellar space to orbit or land on exoplanets, and for the foreseeable future, our envisioned space telescopes, no matter how sophisticated, will not be able to image the planetary surface. However, there is a long-standing and growing excitement on the prospects for the search for life by remote sensing of exoplanet atmospheres to search for gases that might be attributed to life. In the future, astronomers will be able to observe the absorption or emission properties of small, rocky exoplanet atmospheres—globally averaged—to look for "biosignature gases." For a review of the astronomical case for the search for signs of life through biosignature gases, see (15).

Biology research that might give us a better understanding of the gases produced by life on an exoplanet has not had the same cornucopia of discovery to drive new ideas about what life might flourish on alien worlds. Largely, this is because we only have one example of life—life on Earth—to work with. So until very recently, our innovation on the biosignature gases that we might want to look for has lagged the advances in planetary science. Here, we detail the status and direction of the research field of biosignature gases for exoplanets.

EXOPLANET ATMOSPHERES

Exoplanet atmospheres are the key for life detection on a planet beyond our solar system. The premise is that life produces gases as by-products to metabolism, and that some of the gases will accumulate in

[1]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. [2]Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. [3]Rufus Scientific, Herts SG8 6ED, UK.
*Corresponding author. E-mail: seager@mit.edu

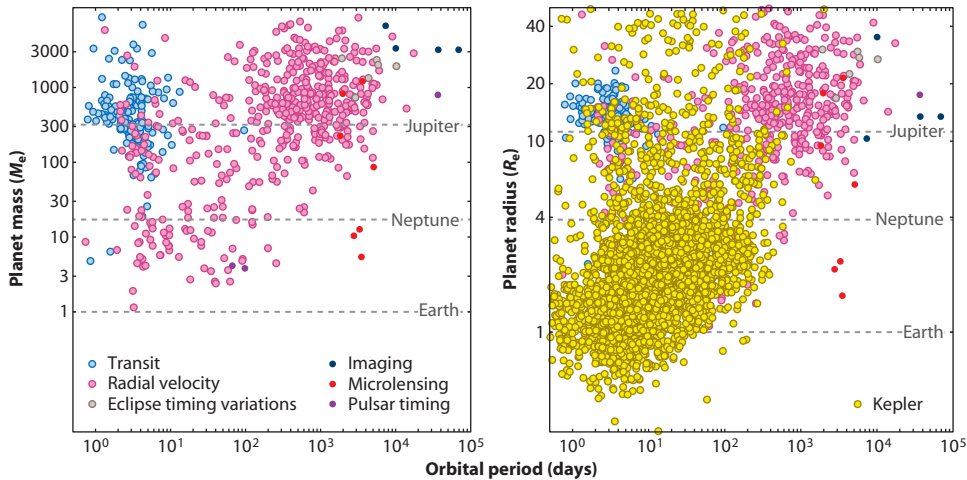Seager *et al. Sci. Adv.* 2015;1:e1500047   6 March 2015

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Fig. 1. Exoplanet discovery space as of 2014. Color coded according to the planet discovery technique. (**Left**) Plotted as mass versus orbital period and not including Kepler discoveries. (**Right**) Plotted as radius versus orbital period (and using a simplified mass-radius relationship to transform planet mass to radius) and shows just how many exoplanets have been discovered, most by the Kepler space telescope. The paucity of planets of Earth's size or mass and orbit emphasizes the challenge of exoEarth discovery with any planet-discovery technique. Figure from (*10*).

a habitable planet atmosphere and in principle can be detected by spectroscopy (Fig. 2). However, we must be able to characterize exoplanet atmospheres to make any progress. Here, our understanding has advanced greatly in the last 20 years, but we are severely limited as to the underlying raw data we can collect from something as small as a shell of gas a few hundred kilometers thick around a faint planet tens of trillions or more kilometers away, where the faint planet is dwarfed by the brightness of the adjacent host star.

Progress and limitations

Exoplanet atmosphere studies have gone from birth to maturity in less than two decades. The first observations were breakthrough successes by novel observational techniques, using telescopes and instrumentation not designed to measure the tiny signals from exoplanet atmospheres (*16–18*). These low signal-to-noise detections, however, could do little beyond a crude temperature estimate or identify one or two of the atmospheric gases present. Some of the claimed exoplanet atmosphere molecular gas detections were challenged (*19, 20*) because observational systematic effects can be of the same order as the signal. At the same time as observational techniques were honed by understanding and removing systematic noise sources in observations, many more bright planets suitable for atmosphere observations were discovered. The discovery lead to dozens of exoplanet atmospheres with very basic measurements and a triumphant collection of exoplanet spectra for four hot giant or sub-Neptune–sized planets (*21–24*).

Now, the field boasts several different atmosphere observation techniques. Most take advantage of transiting planets, using painstaking analysis to extract the spectroscopic signal from the planet's atmosphere from the combined light of planet-star system without having to spatially separate the dim planet from that of its bright host star (Fig. 3). These include transit transmission spectra (*16, 25*) and measuring secondary eclipse spectra in thermal emission (*17, 18*) and reflected light (*26, 27*). We now turn to nontransiting planets. For those planets with short orbital periods and consequent high orbital velocities,

a high spectral dispersion cross-correlation technique has been used to measure atmospheric spectral features, which takes advantage of the planet's orbital motion (and the consequent Doppler shift in the planetary spectrum compared to the stellar spectrum) and a known template of high spectral resolution molecular lines (*28*). Reflected light and thermal phase curves also do not require transiting geometry, but for now are limited to planets close to their star that are bright in reflected light or hot thermally. For giant planets orbiting relatively far from their host stars, ground-based telescopes with adaptive optics and careful post-processing techniques have begun to succeed in measuring near-infrared (IR) atmospheric lines (*29*). Starlight suppression to observe only the planet light is beginning in earnest for giant planets far from the star using large ground-based telescopes (*29*). An impressive, rapid maturation of data interpretation techniques for atmospheric retrieval (*30*) has emerged as adaptations and improvements over established solar system planet atmosphere retrieval techniques to take analysis of the exoplanet atmosphere data as far as it can go both for current data sets (*31–34*) and the exoplanet atmosphere data sets expected in the future.

Despite the progress in exoplanet atmosphere observations and theory, we are severely data-limited in our study of exoplanet atmospheres of any kind. Very few exoplanets are suitable for detailed atmosphere observations. First, the exoplanet and star system have to be close to Earth because they need to be bright enough to achieve high enough signal-to-noise in the observational measurement. The small planets discovered by Kepler (*10*), including about a dozen of Earth-sized planets in their star's habitable zone at several hundred to a couple of thousand light years away, are too distant for their atmospheres to be measured.

Second, the currently most favorable method available to observe exoplanets relies on a fortuitous planet-star alignment that only applies to a small subset of planets: the "transiting exoplanets" that pass in front of (and in most cases also behind) the star as seen from the telescope (Fig. 3). The further a planet orbits from its star, the lower the probability that it shows transits, such that for a planet in an Earth-like orbit about a Sun-like star, only 1 in 200 would show transits.

Third, and a more general statement as to why exoplanet atmospheres observations are so limited, is that even when a planet is suitable, the data we get out are weak and noisy. The smaller the planet is, the worse the data problem becomes. For now, this means most planets whose atmospheres we can study are giant planets or hot planets unsuitable for life as we know it.

To enable atmosphere observations for small planets and overcome the above limiting factors, major investments in facilities to discover small exoplanets and study their atmospheres are coming to fruition in the next decade or two (*15*). The major problem that cannot be avoided is that the small, dim exoplanet (and its even smaller atmosphere) is
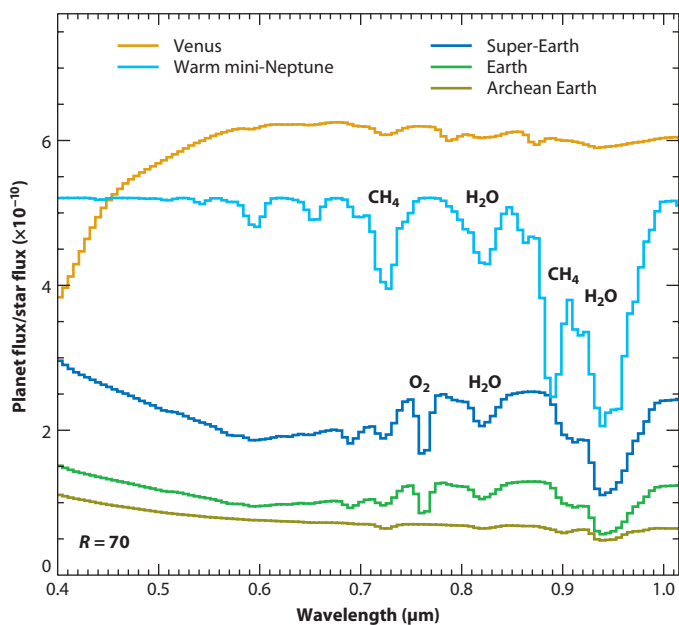
Fig. 2. Simulated spectra of small exoplanet atmospheres. Reflected light spectra are presented in units of planet-to-star flux ratio and are of the spectral resolution anticipated for exoEarths with future space-based starlight-suppression capable telescopes. The Earth spectrum is a model developed to match Earth observations from the EPOXI mission (105), whereas the super-Earth is that model scaled by $(1.5 \, R_\oplus / 1 \, R_\oplus)^2$. The Venus spectrum is a model from the Virtual Planet Laboratory (VPL; http://depts.washington.edu/naivpl/). The Archean Earth spectrum is a model of the inhabited Earth before the rise of oxygen in its atmosphere (87). The sub-Neptune ("mini-Neptune") model is a 2.5 $R_\oplus$ Neptune-like planet at 2 AU from a solar-twin star (R. Hu, personal communication). The spectra have been convolved to $R = 70$ spectral resolution and binned with two pixels per resolution element (Nyquist sampling). Figure courtesy of A. Roberge.
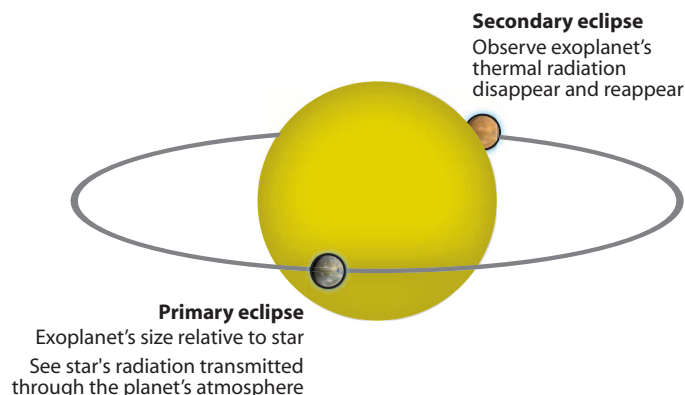

Secondary eclipse
Observe exoplanet's thermal radiation disappear and reappear

Primary eclipse
Exoplanet's size relative to star
See star's radiation transmitted through the planet's atmosphere

Fig. 3. Schematic of a transiting exoplanet. When the planet goes in front of the star as seen from a telescope (a "transit" or "primary eclipse"), the starlight drops in brightness by the planet-to-star area ratio. In addition, the starlight passes through the planet atmosphere and planet atmosphere spectral features are imprinted on the stellar spectrum. This is called transmission spectroscopy. When the planet goes behind the star, the planet disappears and reappears, adding either reflected light or thermal emission to the combined planet-star radiation. This is referred to as secondary eclipse photometry or spectroscopy. Dozens of transiting exoplanet atmospheres have been studied, taking advantage of the fact that the planet and star do not need to be spatially separated as projected on the sky.

next to a big, bright star, and so any technique needs to work around the star.

A sub-Neptune case study

The exoplanet GJ 1214b makes a good case study to illustrate the excitement, achievements, and limitations of exoplanet atmosphere science. Discovered in 2009, GJ 1214b remains one of the most enigmatic exoplanets known (35). GJ 1214b's size (2.8 times Earth radius), mass (6.3 Earth masses), and average density (1.6 ± 0.6 g cm^{-3}) (36) put it in a class of planets in between terrestrial planets (predominantly rocky) and giant planets (predominantly H/He), but one whose formation and even composition is not known (5, 6).

For GJ 1214b, its mass and size yield an average density that is not definitive in describing the planet's bulk composition. That is, the planet's average density is compatible with many planetary compositions. The only certain statement is that the planet must be composed of a large amount of low-density material (37). The planet could be a water world, an envisioned planet with 50% by mass or more water; the planet could be predominantly rocky with a pure hydrogen envelope that arose from outgassing during planet formation; or the planet could be described as a "sub-Neptune," a smaller version of Neptune with a hydrogen and helium envelope formed from accreting H and He gas from its surroundings. All yield the same mass and density, as do any intermediate combination of these end-member scenarios (38).

This large ambiguity in the assessment of the bulk combination of GJ 1214b and many other exoplanets is discouraging but speaks to a theme in exoplanets. Often, the physical properties of a planet fall into a category where there are no unique interpretations, even with the most precise measurements (in this case, mass and radius). A counter example is a very dense small planet must be predominantly rocky, but even in that case with just the two measured parameters of mass and radius, the detailed composition and interior structure cannot be ascertained. Note that a measurement of gravitational moments used to determine the interior structure of solar system planets is not accessible for exoplanets, nor are the seismological approaches available for studies of the interior of the Earth. [For a recent review of planet interior structure and ambiguities, see (39, 40).]

The exoplanet community had hoped that atmosphere measurements via transmission spectroscopy would possibly be able to discriminate among the scenarios for GJ 1214b's interior bulk composition (37, 38). An atmosphere dominated by H_2 or H_2/He would be puffy (have a large scale height), and with no clouds, it would show deep spectral features. In contrast, a clear atmosphere dominated by a higher–molecular weight species (H_2O, N_2, CO_2) would have a smaller scale height than for the hydrogen atmosphere, resulting in an atmosphere with small "compressed" spectral features (Fig. 4). Clouds were not expected because at GJ 1214b's temperature of ~580 K (predicted from a simple calculation of stellar heating and the main elements in planet atmospheres), no condensates were expected at all or to exist in high enough abundance to form blanketing clouds.

Early data from the European Southern Observatory's Very Large Telescope and others showed a hint of water vapor in a high–molecular weight atmosphere. Although the observational signal was not statistically significant, it was incredibly intriguing (41), and it was enough to motivate more data with a sobering realization of just how much telescope time resources would have to be invested in each individual planet atmosphere of interest. An unprecedented amount of Hubble Space Telescope time (15 transits over 60 orbits) revealed a high signal-to-noise
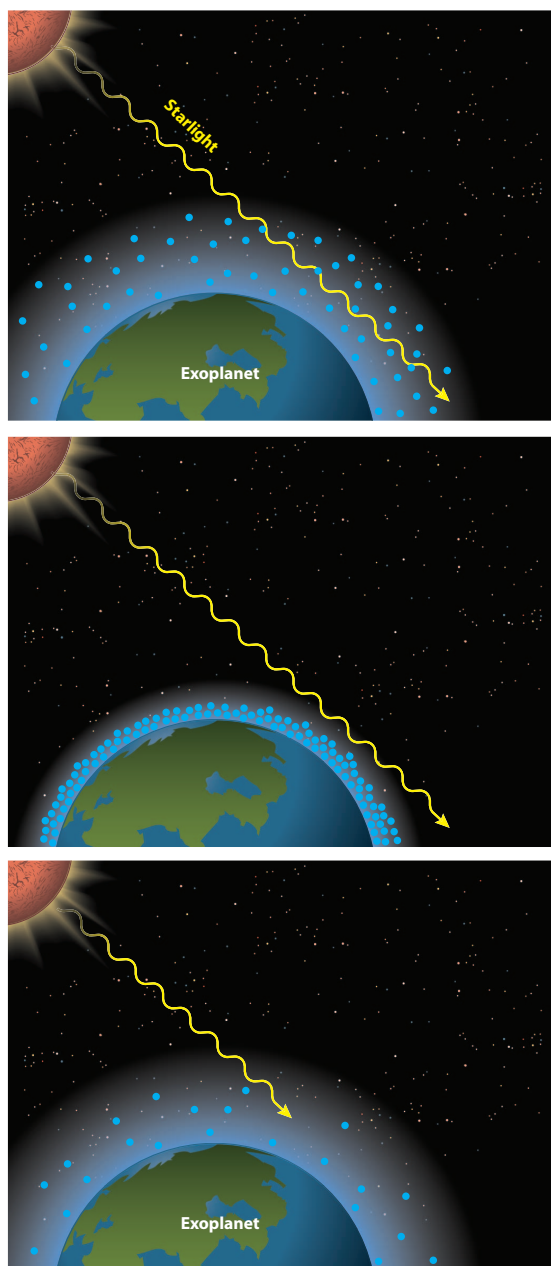
Fig. 4. Schematic of a transmission spectrum. Transmission spectra are created by planet atmosphere absorption imprinted on starlight passing through the planet atmosphere. (**Top**) Shown are a variety of different cases: deep and wide spectral features are expected from a low–molecular weight atmosphere, which presents a relatively large volume to be sampled. (**Middle**) In contrast, only narrow, shallow spectral features are expected from a high–molecular weight atmosphere, which results in a limited atmosphere to be sampled by the starlight. (**Bottom**) Clouds block starlight and may entirely prevent sampling of the dense part of the atmosphere where spectral lines form. Other situations are also possible. Many exoplanet spectra including (22) find no spectral features, consistent with clouds. Figure credit: S. Seager and D. Beckner.

resolution spectrum (22). The spectrum showed no atmospheric spectral features at all. The most likely interpretation is that an opaque layer of clouds is blocking the deeper part of the atmosphere from

view, and the atmosphere that is visible above the clouds is too thin for any spectral features to register (Fig. 5). Clouds are generally featureless at the spectral resolution for exoplanet atmosphere data because rotational and vibrational bands are suppressed in a solid compared to a gas, and features are also weakened by large ranges of particle shapes and sizes within a given cloud (42). In the future, we may be able to access small near-IR features with the next-generation space telescope James Webb Space Telescope (JWST) (43), or broad spectral slopes at blue visible wavelengths may also be helpful (21, 44).

The featureless spectrum of GJ 1214b is so puzzling that people have postulated extreme scenarios to explain the data. Perhaps GJ 1214b has lost virtually its entire atmosphere, via atmospheric escape processes, and we are observing its surface. Perhaps, the atmosphere is of such high metallicity that a different chemical equilibrium regime can explain the data (45). Perhaps, GJ 1214b has a He-dominated atmosphere, where just the right conditions enabled the lighter element H to escape but He to remain (helium has no prominent IR or visible absorption features for current instrumentation) (46). Thus, rather than help decide between three scenarios (water world, hydrogen atmosphere, or sub-Neptune), spectral studies have actually increased our uncertainty with more options. If the planet atmosphere observations were not limited to the transiting configuration, more progress might be made.

The lesson learned from GJ 1214b and other exoplanets is that even if we have a planet that appears to be a promising candidate for atmosphere observations, an observational assessment of the planet's atmosphere may just not work out because the planet's physical properties lay hidden beneath too few measurements or have an ambiguity in their interpretation. Thus, although the future holds promise for a handful of small, rocky exoplanets in their host star's habitable zone, we may find that we have too little data on a planet of interest or that the data may not tell us what we want to know. This motivates us to cover all the possibilities of true and false signatures for life, so we do not miss an opportunity within the small group of planets we have for observations. The next two sections, therefore, examine what we know about the gases life makes on Earth, and their detectability on Earth and other rocky planets.

MODERN REFLECTIONS ON A HISTORY OF BIOSIGNATURE GASES

Exoplanet atmosphere observations are established, and despite their limitations for planet characterization (described in Exoplanet Atmospheres), the vision for an opportunity to observe small planet atmospheres for biosignature gases in the future is real. A biosignature gas is defined as one that is produced by life and accumulates in a planet's atmosphere to detectable levels. Any kind of ab initio approach to predicting what biosignature gases might be is so challenging that nearly all work done to date basically follows the thought, "We know what Earth life produces, so what might Earth life's products look like if transplanted to another, slightly different, Earth-like world?" (Here, "Earth-like" refers to a planet with about the same size and mass as Earth, with oceans and continents, a thin N_2-CO_2-O_2 atmosphere, and a radiation environment similar to that of Earth's. We use "exoEarth" to refer to habitable planets that differ from Earth.) Gases studied in this context include oxygen, the otherwise unexplained simultaneous presence of gases out of thermodynamic equilibrium (specifically methane with oxygen), methyl halides, sulfur compounds, and some other gases.
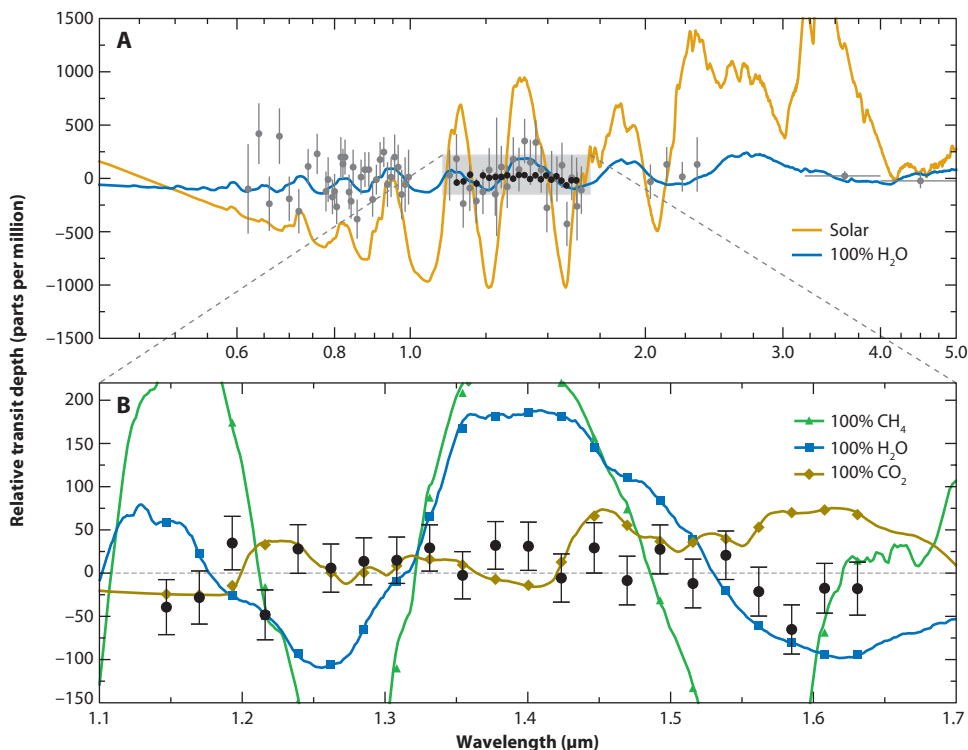
Fig. 5. Transmission spectra of GJ 1214b. Models are represented by solid curves. No spectral features are detected in the most recent data set, because a straight line can be fit to the data (bottom panel). Figure credit and more details in (22).

In this section, we review the two main thrusts historically described for biosignature gases. In the next section, we move on to review a broader collection of work, including some that tries to break away from the "terracentric" focus.

Oxygen: Earth's canonical biosignature gas

Oxygen (O_2) is considered Earth's most robust biosignature gas (47, 48). O_2 is present in Earth's atmosphere to 20% by volume. O_2 is a reactive gas with a short atmospheric lifetime that without continual replenishment by photosynthesis in plants and bacteria would be present only in trace amounts in Earth's atmosphere, ten orders of magnitude less than present today (49). Any exoplanetary observer seeing oxygen in Earth's spectrum would know that some very exotic, non-geological chemistry must be producing it, hence the foundational paradigm of O_2's robustness of an exoEarth biosignature gas.

There is no precise explanation for Earth's value of O_2 atmospheric abundance. In general, we have high atmospheric O_2 because of a combination of the presence of photosynthesizing life and the burial of some of that life as carbon, but what sets the precise level is not known. Over the last 500 million years, photosynthesis has not changed radically, and yet, the O_2 level has changed from less than 15% in the Devonian to greater than 30% in the Carboniferous (50, 51).

To explain in more detail, photosynthesis captures the carbon in CO_2 into biomass, releasing oxygen. However, decay of plant material consumes oxygen, combining O_2 with biomass to regenerate CO_2. If this cycle were perfectly efficient, no O_2 would accumulate. Earth has free oxygen in its atmosphere because a small fraction of the carbon that is turned into biomass is not returned as CO_2, but is trapped and

sequestered in soils and rocks. For most of Earth's history, very little carbon must have been sequestered, and the resulting atmospheric O_2 levels were low. (It is not clear if the fraction buried was small or that there was just less photosynthesis, or both.) In the late Precambrian, this changed; much more carbon was trapped, allowing the development of the modern, high-O_2 atmosphere. The evolution of land plants, and consequent doubling of O_2 production, may have been a factor in the increase of atmospheric O_2. Other hypotheses have included the following: a surge in oceanic plant productivity occasioned by the thawing of a snowball Earth in the late Precambrian, leading to high rates of burial; changes in plate tectonics leading to more subduction of ocean floor biomass; or the gradual oxidation of the crust, which meant that oxygen would not be consumed by oxidizing surface minerals such as sulfides. We need not, however, point to marked geochemical changes to explain significant changes in oxygen levels. The environmental change might have been quite small, as witnessed by the hypothesized effect that the evolution of a single enzyme in fungi had on oxygen levels. Around 350 to 400 million years ago, plants evolved the ability to make lignin, the polymer that strengthens wood and gives it resistance to weather and insect attack, allowing land plants to grow much larger (52). About 30% of land plant biomass is lignin. Lignin is very tough, however, and for a long time, no organism had evolved an enzyme to break it down, so lignin was just buried, becoming coal seams (hence the name of the period—Carboniferous). The Carboniferous was the period with the highest atmospheric oxygen levels (a higher percentage of biomass buried would lead to higher O_2 levels). At the end of the Carboniferous, fungi evolved ligninase enzymes that allowed them to use lignin as nutrient (53), and so, lignin could be metabolized and the carbon turned back into CO_2 by reacting with O_2, instead of being buried. At the end of the Carboniferous, atmospheric oxygen fell to ~15% (51). It is plausible to suggest that these events are linked, and the evolution of one family of enzymes in a group of fungi caused a 50% fall in atmospheric oxygen levels.

There are abiotic routes for substantial amounts of O_2 production. For example, photodissociation of water vapor in a runaway greenhouse with H escaping to space could lead to detectable O_2 levels (54). This situation could be identified by an atmosphere heavily saturated with water vapor. A different abiotic production pathway route is one where O_2 accumulates in a dry, CO_2-rich planet with weak geochemical sinks for O_2, a case that could be identified via strong CO_2 and weak H_2O features (55–57). Indeed, any exoplanet scenario where O_2 sinks are argued to not be present will enable accumulation of abiotically produced O_2 after its creation from photodissociation by-products.

Until recently, the exoplanetary science community has assumed O_2 (and its abiologically produced photochemical product ozone O_3) as "obviously" the best case for a biosignature gas in the search for life

beyond our solar system. For any future detection, we have to ask if the data quality is sufficient to unambiguously identify O_2 and other atmospheric gases, which would set the environmental context in which we are confident that the O_2 is not being geochemically or photochemically generated (58). This is easier said than done because of a wide variety of possibilities in terms of atmospheric mantle, surface and atmospheric chemistry, and photochemistry scenarios surely allowed by exoplanets.

Atmospheric thermodynamical disequilibrium disfavored

An early mainstay concept in the search for life by atmospheric sensing originated in the very first discussions on the topic: the idea of a system at thermodynamic disequilibrium being an atmospheric biosignature (59, 60). In particular, Lippincott et al. (61) suggested that a deliberate search for materials substantially out of thermodynamic equilibrium was a strategy to search for life. They suggested that the combination of hydrocarbons and molecular oxygen on the Earth's surface was an example of such a clear chemical disequilibrium (a redox disequilibrium) and, hence, a sign of life. (However, Lovelock was concerned with the components of life rather than their atmospheric waste products.) Methane (CH_4) as the hydrocarbon to be contrasted with O_2 was first recognized as a thermodynamic sign of life by Lippincott et al. (61) with the first systematic thermodynamic equilibrium calculations on the atmospheres of Earth, Mars, and Venus. They found that CH_4 is strongly out of thermodynamic equilibrium on Earth, as are H_2, N_2O, and SO_2, although none are unambiguous signs of life due to production by geochemical processes (with the possible exception of N_2O). By 1975, (61) was being cited as support for the idea that the O_2/CH_4 disequilibrium was strong evidence for life (62) at a meeting in which CH_4 as a biosignature gas also seemed to be established (62, 63).

There are several arguments against the use of thermodynamic equilibrium, including a redox disequilibrium pair, as a life indicator. The first point is that almost any gas other than N_2 and CO_2 in Earth's atmosphere, however generated, is out of thermodynamic equilibrium because of the Earth's high O_2 levels. So, the argument that Earth's atmosphere is out of thermodynamic equilibrium reduces to a statement about the high levels of Earth's atmospheric O_2. Even in an environment devoid of O_2, significant thermodynamic disequilibrium can be generated by geochemical or photochemical processes. For example, volcanism produces both SO_2 and H_2S, a gas mixture out of thermodynamic equilibrium at terrestrial surface conditions, as reactions between the two will form water and elemental sulfur. Detecting both H_2S and SO_2 in an exoplanet atmosphere could therefore be either a sign of life or just a sign of volcanism. Impact events can produce CO, which is out of thermodynamic equilibrium with O_2, CO_2, and CH_4 at Earth surface temperatures and pressure (64, 65). In addition, it is likely that one member of a disequilibrium pair will be present in small amounts, and so will not be detectable with the space-based telescope capabilities we envision for the coming decades [for a criticism of the detectability of Earth's O_2-CH_4 redox pair through time, see (15)].

In summary, for any future observed O_2 and/or the thermodynamic equilibrium, we have to observe as much as possible about a planet and its atmosphere, and using a wide range of model scenarios estimate the chance that abiological chemistry could have generated the observations that we see. Thermodynamics is part of this, but far from the defining feature.

A VAST ARRAY OF GASES PRODUCED BY EARTH'S LIFE AND THEIR POTENTIAL ON OTHER WORLDS

The chemicals produced by life on Earth are numbering in the hundreds of thousands [estimated from plant natural products (66), microbial natural products (67), and marine natural products (68)]. However, only a subset of hundreds are volatile enough to enter the atmosphere at more than trace concentrations. Only tens accumulate to high enough levels to be considered as being remotely detectable for astronomical purposes. Out of this high-level subset, only a few are spectroscopically active enough to be considered as detectable by a remote space telescope looking at Earth as an exoplanet.

Apart from oxygen, these biosignature gases range from highly abundant gases in Earth's atmosphere that are either already existing or predominantly produced by geochemical or photochemical processes (N_2, Ar, CO_2, and H_2O) to those that are relatively abundant and attributed to life (N_2O, CH_4, H_2S, and H_2S) to gases that are weakly present but may play important roles in atmospheric processes (DMS and CH_3Cl) to gases that are present only in trace amounts including the hundreds of minutely present volatile organic compounds released by trees in a forest or fungi in the soil. Given that O_2 may not be present on an exoEarth with life and the chance of not being able to observationally identify thermochemical disequilibrium or attribute it to life (Exoplanet Atmospheres), the next step is to consider a wider range of gases produced by life on Earth and what to do with them in an exoEarth context.

We choose to focus on gases emitted by life, rather than solid products or features (such as the green photosynthetic pigments, which are not presently detectable) or technosignatures (such as chlorofluorocarbons). All life on Earth makes gas products, and basic chemistry suggests the same will be true of any other plausible biochemistry. The question is: What products?

Earth's biosignature gases, organized

Out of the promising numbers and variety of gases produced by life on Earth, there appears to be a conundrum when considering their potential as biosignature gases for exoplanets (69). On Earth, the most abundant biosignature gases (for example, CH_4) can also be produced abundantly from abiological sources and will therefore have false positives in an exoplanet context. In contrast, the biosignature gases that seem to be unique to life (for example, DMS released by oceanic plankton) are present only in tiny quantities. Earth's favored biosignature gas O_2 may be unique in being both abundant and non-geological, but life on other worlds may not make O_2.

The most abundant gases produced by life on Earth will be seriously contaminated with false positives. These are gases produced when life exploits a chemical potential energy gradient (usually a redox gradient) that is geochemically stable. Such gradients arise as follows. Two materials (such as hydrogen and carbon dioxide) are produced by different geochemical processes and come together in one place. Their reaction is thermodynamically favored but kinetically inhibited—their reaction cannot happen at ambient temperatures and pressures. Life exploits this by catalyzing the reaction. Gas products of such reactions include CH_4, N_2O, and H_2S [these are called type I biosignature gases by (69)]. Such gases are abundant because they are created from chemicals that are plentiful in the environment. However, as biosignatures, they are fraught with false positives. Not only does geology have the same molecules to work with as life does, but whereas a given

redox reaction may be kinetically inhibited in one environment, and thus will proceed only when activated by life's enzymes, in another environment with the right conditions (temperature, pressure, concentration, and acidity), the same reaction might proceed spontaneously.

An example of a "chemical energy gradient" biosignature gas is methane. At the sea floor, methanogens extract energy from hydrogen [released by hot fluids over cracked rocks (serpentinization)] and carbon dioxide (mixed into the ocean from the atmosphere) and generate methane as a by-product gas $H_2 + CO_2 \rightarrow CH_4 + H_2O$. However, methane is an ambiguous biosignature, because it is also released volcanically from hydrothermal systems (although presently, that is a small contribution to Earth's methane budget). Methane has been extensively studied as a biosignature gas on exoplanets (70–80). The recent confirmation of methane in the atmosphere of Mars (81) is a good example for both the consideration of CH_4 as a biosignature gas because it is photochemically unstable and must be actively produced, but it is also an example for a false positive because CH_4 could be produced geologically.

On Earth, life exploits any chemical gradient possible (Fig. 6). A great example of this versatility is the prediction (82) and discovery 30 years later (83) of bacteria capable of anaerobic ammonia oxidation, the "annamox" reaction.
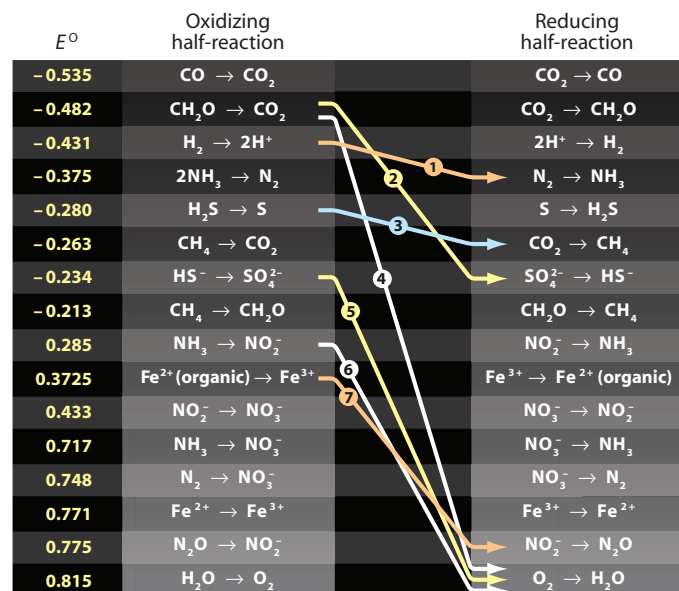

Fig. 6. Schematic illustration of microbial-used chemical potential energy gradients. Redox half-reactions are shown in order of their electrode potential (in volts) at pH 7.0, calculated from the standard electrode potentials for the reactions (106). Each reaction is shown as an oxidation half-reaction (**left side**) and as a reduction half-reaction (**right side**). If the oxidation of molecule A in the left column is above reduction of a molecule in the right column, then the oxidation of A can be coupled to the reduction of B yielding energy. Thus, arrows drawn between half-reactions yield energy if they run downward from left to right, and the length of the arrow indicates the amount of energy released. Coupled reactions noted in color are as follows: (1) nitrogen reduction (also nitrogen fixation or ammonia synthesis); (2) sulfate reduction (also anaerobic biomass oxidation); (3) anaerobic sulfide oxidation; (4) aerobic biomass oxidation/oxidation of organic matter/oxidation of carbohydrate; (5) aerobic sulfide oxidation; (6) aerobic ammonia oxidation; (7) aerobic iron oxidation.

The biosignature gases that do seem to be uniquely produced by life—that is, are unlikely to have false positives—are produced in tiny quantities that may be too low for the gas to accumulate to detectable levels in the exoEarth atmosphere. This class of biosignature gases appear to be special to particular species or groups of organisms, and require energy for their production [called type III by (69)]. They are produced for organism-specific reasons and are highly specialized chemicals not directly tied to the local chemical environment and thermodynamics. One example is dimethyl sulfide (CH_3SCH_3 or DMS) produced by plankton. Predatory plankton produce DMS as a breakdown product of dimethyl sulfoniopropionate (DMSP) when they eat phytoplankton, but it is unknown as to why phytoplankton produce DMSP (84). Other biosignature gases in this category of energy-requiring specialized by-product gases include methanethiol CH_3SH (85), methyl chloride CH_3Cl (86), and organic sulfur compounds [CS_2, OCS, CH_3SH, CH_3SCH_3, and $CH_3S_2CH_3$ (87)]. Some of these gases, under the right conditions of excess production or favorable ultraviolet (UV) flux conditions, could accumulate to hypothetically detectable levels.

A category with few biosignature gases, described here for completeness, includes by-products from biomass building: energy-requiring reactions that capture environmental carbon [and to a lesser extent other elements; called type II biosignature gases by (69)]. The dominant terrestrial example is O_2 produced by photosynthesis, which gains energy from sunlight. Sulfate is produced from H_2S photosynthesis, but because sulfate is not a gas, it cannot enter the atmosphere as a biosignature.

The inevitable terracentricity of exoplanet atmosphere models for biosignature gases

Given a list of gases produced by life on Earth, one wants to be able to explore the potential of these gases as biosignature gases in an atmosphere of a distant exoEarth. Because observations are years to decades off, model atmosphere calculations are used to explore possibilities [for example, (70–80)].

The key input for the model atmospheres are the biofluxes, the gas flux emitted by life (as net gas output per square meter of surface per unit time). On Earth, biofluxes from terrestrial ecosystems have been measured directly. Measurements for gases relevant for exoplanets include methane (88), sulfur gases (89, 90), methyl chloride (91, 92), nitrogen oxides (93, 94), ammonia (95), and many others (96).

The challenge in microbial fluxes for models of exoplanets is that bioflux measurements are not ideal representations. The interface of microbiology and exoplanetary science is not clean. Environmental flux measurements usually relate to just one location that may be atypical of planet as a whole. Extrapolation of one measured bioflux of interest is therefore problematic. In addition, the same gas may play different roles in different ecosystems, and comparing its flux between them is therefore invalid. For example, the production of CH_4 by swamps on Earth can vary from little to prodigious amounts of CH_4. For environments where organic matter, water, and other nutrients are abundant (such as swamps), CH_4 flux rates of methane can reach 2 to 3 µg C m^{-2} s^{-1} (97, 98), which if scaled to a global flux would be 45 Pg/year, compared to the global production of oxygen of ~200 Pg/year (99). For Earth, a globally integrated model of gas flux can be built by integrating many such measurements, but even this is difficult because the list of sources and sinks is never complete. For an exoplanet where all sources and sinks are unknown, such integration is not practical.

Despite the caveats to measuring Earth's biofluxes, and despite not having a reason to believe Earth's biofluxes to be universally applicable, terrestrial biofluxes have enabled researchers to make progress. One model-independent finding is that the UV flux output of the exoplanet host star really matters because of its control over the atmospheric photochemical processes that destroy biosignature and other gases. So, planets orbiting stars with low UV radiation environments are more likely to have biosignature gases of any kind accumulating in their atmospheres (56). Another interesting and largely model-independent finding pertains to sulfur gases. Abundant sulfur biofluxes will not accumulate in the atmosphere but will drive photochemistry either to acetylene and other hydrocarbons (87) or to sulfur hazes that will obscure the atmosphere (100).

We have attempted to move beyond models based on observed terrestrial fluxes by inverting the problem, and asking what flux of gas is needed in an exoEarth atmosphere to be "detectable" in a simulated spectrum data set, and whether the biomass required to produce the gas abundance is plausible (69). Would a realistic few-micrometer-thick layer of microbes produce enough gas or would it have to be an implausible few-kilometers-thick layer? This method also runs up against terracentric assumptions, but ones that may be less specific to modern ecology. We started from the empirical finding that microbial life requires a minimum power consumption (energy flux through metabolism) to survive, and that this minimum power is dependent only on temperature and is based on the Arrhenius law (101). We then used this relationship in a conservation of energy statement to connect a biomass to a bioflux: the minimum energy needed per unit mass dictates a by-product gas output per unit mass because the energy released by a gas-generating reaction, and hence the energy released per gram of gas released, is a basic thermodynamic calculation and not dependent on any biochemical details. However, this is not divorced from terrestrial biochemistry because the rate constants in the Arrhenius equation are derived from measures made on terrestrial microbes. The rate constants ultimately relate to the collision rates between molecules (which are universally related to temperature) and to the energy needed to break molecular bonds; this second term depends on the molecules involved and therefore ties this calculations to the molecules that make up Earth life. Thus, although more general than measuring the production of specific gases by specific ecosystems on Earth, this calculation still requires the assumption that alien life has the same sort of chemical constituents as our life. In summary, simulating data for exoplanet atmospheres that have hypothetical life-produced biosignature gases may always remain terracentric to some degree.

A PATH FORWARD FOR NEW WORLDS AND NEW ENVIRONMENTS AT THE INTERFACE OF CHEMISTRY AND PLANETARY SCIENCE

The terracentric approach—considering a planet with Earth's characteristics including atmospheric mass and composition (today or in the past), and calculating the accumulation of biosignature gases under slightly different scenarios (such as other star types)—is a natural starting point and has been studied extensively (A Vast Array of Gases Produced by Earth's Life and Their Potential on Other Worlds). This terracentric focus has largely exhausted the small Earth-like area of the much wider parameter space of other potential planetary scenarios. Attempts to escape from terracentricity have run into terrestrial lim-

itations of another form. What of planets substantially larger or smaller than Earth, with much more massive atmospheres, or with substantially different atmospheric composition? And what of life that has different biofluxes from the terrestrial biosphere, either because of a different ecology (addressed for the specific models of the Archean Earth, but not otherwise modeled) or even a basically different chemistry? Expanding beyond considering terrestrial planetary characteristics and terrestrial biology presents formidable challenges and has blocked progress.

There are two separate but related paths forward. One path forward is to continue the modeling approach with biofluxes as free ranging parameters and detailed photochemistry models while considering planets more and more different from Earth, no matter how vast the parameter space of imagined scenarios might be. This exhaustive modeling endeavor has inadvertently begun for O_2, with the resurgent consideration of false positives and different possibilities in terms of atmospheric mantle, surface and atmospheric chemistry, and photochemistry scenarios. Forays are headed in the right direction [for example, (87)].

An example of the first path forward for biosignature gases on exoEarths with a completely different atmosphere than Earth is the case of rocky exoplanets with hydrogen-dominated atmospheres, in the form of molecular hydrogen H_2 (102). Although not yet observed, such planets are theoretically anticipated. Outgassing of H early in a rocky planet's history is expected based on the makeup of planet-forming building blocks and the temperatures and pressures associated with newly formed planets (103), and some planets are expected to have high enough surface gravity or cold enough atmospheres to hold on to H_2. Determining whether a biosignature gas could accumulate in H_2-dominated atmospheres is a photochemistry problem. We considered a variety of gases and their lifetimes in an H_2 atmosphere under different conditions. We found that many gases could accumulate, and the lifetime limiting factor for most gases is destructive reactions with H, itself produced when stellar UV photons split up H_2 via a mechanism catalyzed by H_2O. (Some gases were more likely to be destroyed by O, a product of the photolysis of water.) Our understanding of photochemistry is based on universal chemical principles, so as long as the complete set of relevant reactions and their rates are included, the model can be tailored for any imagined scenario.

A second path forward takes as general a view as possible—to consider all small molecules, not just those that are produced by life on Earth, but all of those that are both stable and volatile at a wide range of habitable atmospheric temperatures and pressures (Fig. 7) (104). With this in mind, we would like to catalog and distill all of the possibilities of biosignature gases. This turns the problem of identifying candidate biosignature gases from one of cataloging what life does on Earth (primarily a problem in microbiology) to one of cataloging chemicals and their properties (primarily a problem in chemistry). Recall that terrestrial biochemistry produces thousands of volatile molecules, and their role, and why life chose those particular molecules to fill that role, is often unknown. So ultimately, we would seek to have an exhaustive catalog of volatiles linked to an understanding of their atmospheric and surface (abiological) chemistry, photochemistry, and spectral properties (104). From this, we can select both promising chemical candidates and promising ways to search the spectrum that could capture the most diverse range of such candidates.

The appeal of the "all-small-molecule" approach is that it is independent of terrestrial biochemistry. The only assumption is one
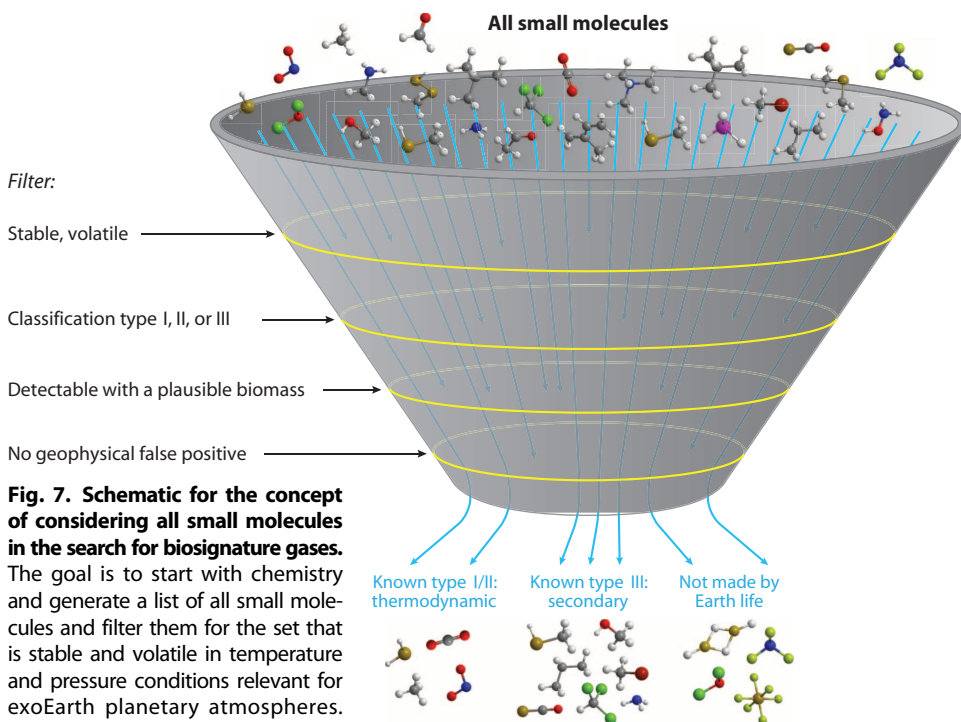
Fig. 7. Schematic for the concept of considering all small molecules in the search for biosignature gases. The goal is to start with chemistry and generate a list of all molecules and filter them for the set that is stable and volatile in temperature and pressure conditions relevant for exoEarth planetary atmospheres. Further investigation relates to the detectability: the sources and sinks that ultimately control the molecules' accumulation in a planetary atmosphere of specific conditions as well as its spectral line characteristics. Geophysically or otherwise generated false positives must also be considered. In the ideal situation, this overall conceptual process would lead to a finite but comprehensive list of molecules that could be considered in the search for exoplanet biosignature gases. Figure credit: S. Seager and D. Beckner.

based on chemistry, that life uses chemistry and metabolism to store energy and outputs metabolic by-product gases. After all, we do not see what life is or how it operates, just what life does, that is, metabolizes. The chemicals considered would still have to be integrated into models of planetary chemistry and photochemistry, in and of itself a very substantial task.

SUMMARY AND PROSPECTS

We have sketched the extraordinary diversity of planetary environments that are being discovered, and reviewed the key features in modeling the signs of life in those environments. There is a deep interest in discovering new worlds and new life, and people will continue to search and speculate. However, the amount of data we have on the handful of planets found by the first generation of planet characterization methods is very scant. With current technology, we would not yet have even detected Earth, let alone have the technology to hint that it was inhabited, if we were astronomers living on a planet orbiting the nearest star.

Approaches to detecting life have inevitably been centered on Earth life and its properties because this is the only example of life that we know. The terracentric approach is a natural starting point and has been studied extensively. Attempts to move away from terracentricity have run into their own different terrestrial assumptions. The work done to date has been able to illuminate a few truths—the fate of sulfur biosignature gases and the accumulation of biosignature gases in different

UV environments—and to provide some initial insights into possibilities for terrestrial biosignature gases in highly non–Earth-like atmospheres such as ones dominated by hydrogen. This work will continue.

No single gas, not even O_2, is a definitive biosignature on its own. Identification of a volatile in a planetary atmosphere as a likely product of life needs us to understand the chemical context of the gas, including other atmospheric components (where they can be detected), but also likely planetary chemistry and surface environment. Extensive photochemical exploration, either of alternative atmospheres (102) or specific chemical classes (87), could be extended to other environments and chemistries with the right photochemistry model and a clear understanding of sources and sinks.

The future for the first tentative biosignature gas detections may not be far off if we are lucky. Within the next decade, we look forward to the launch of NASA's TESS (Transiting Exoplanet Survey Satellite) planet discovery mission and the possibilities of characterizing small planet atmospheres with the NASA/European Space Agency JWST, and the construction of large ground-based telescopes with mirror diameters in the 20- to 40-m range. The anticipated numbers of exoEarth planets with atmospheres accessible for observations remain small but hopeful for the next decade. For assessing the presence of life beyond Earth, we may have to await a later generation of space telescopes designed to systematically search the nearest dozens to hundreds of stars (15).

There is therefore time for an ambitious way forward for identifying all viable biosignature gases, through a systematic, exhaustive study both from the view of molecules (there is no shortage) and of planetary environments and where the candidate biosignature gas molecules would accumulate and survive. The near-term goal is to understand which molecules could be biosignature gases in atmospheres of exoplanets; a systematic table of chemicals made by life will give a starting point for predicting which molecules are stable, volatile, and detectable remotely by space telescopes.

However, even this wider understanding of the possibilities, coupled with greatly increased data quantity and quality, will not lead to certainty. Rather, we must accept that with remote observations, our inference of the existence of life on another world will be probabilistic, an estimate of our confidence that life is the only reasonable explanation of the atmospheric chemistry of an exoplanet.

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