

Astro2020 Science White Paper

A Balancing Act: Biosignature and Anti-Biosignature Studies in the Next Decade and Beyond

Thematic Areas: ☒ Planetary Systems

Principal Authors:

Name: Chester Harman

Institution: Columbia University; NASA GISS
Riverside

Email: chester.e.harman@nasa.gov

Name: Edward Schwieterman

Institution: University of California,

Email: eschwiet@ucr.edu

Co-authors:

Vladimir Airapetian (NASA GSFC and American University, DC); Daniel Apai (University of Arizona); Giada Arney (NASA GSFC); Derek Buzasi (Florida Gulf Coast University); Hinsby Cadillo-Quiroz (Arizona State University); Bill Danchi (NASA GSFC); Shawn Domagal-Goldman (NASA GSFC); Chuanfei Dong (Princeton University); Courtney Dressing (University of California, Berkeley); Ryan Felton (Catholic University of America, NASA GSFC); Theresa Mason Fisher (Arizona State University); Kevin France (University of Colorado, Boulder); Dawn Gelino (NASA Exoplanet Science Institute, Caltech); Hilairy E. Hartnett (Arizona State University); Paul Kalas (University of California, Berkeley); Stephen R. Kane (University of California, Riverside); Nancy Y. Kiang (NASA GISS); Jinyoung Serena Kim (University of Arizona); Ravi Kopparapu (NASA GSFC); Mercedes López-Morales (Center for Astrophysics | Harvard & Smithsonian); Jacob Lustig-Yaeger (University of Washington); Niki Parenteau (NASA Ames Research Center); Seth Redfield (Wesleyan University); Chris Reinhard (Georgia Institute of Technology); Tyler D. Robinson (Northern Arizona University); Sarah Rugheimer (University of Oxford); Linda Sohl (Columbia University and NASA GISS); Arif Solmaz (Çağ University); Keivan Stassun (Vanderbilt University); Melissa Trainer (NASA GSFC); Amanda R. Truitt (Los Alamos National Laboratory); Kostas Tsiganidis (Columbia University and NASA GISS); Kevin Wagner (University of Arizona); Sara Walker (Arizona State University)

Abstract:

We endorse the findings and recommendations published in the National Academy reports on Exoplanet Science Strategy and Astrobiology Strategy for the Search for Life in the Universe. This white paper extends and complements the material presented therein by elaborating on the need for (and overlaps within) a quantitative biosignature identification and assessment framework that uses prior knowledge and context to produce a numerical estimate for the likelihood that a given world has life. This provides a comprehensive means to weigh planetary habitability alongside potential biosignatures and their respective false positives. Quantitative frameworks for biosignature detection can inform the needed observational capabilities for future exoplanet surveys with a (partial) focus on detecting habitability and life. In general, planetary

(and stellar) characterization over broad wavelength ranges will reduce ambiguities and increase our confidence that putative spectroscopic biosignatures are produced by life.

Motivation

The last decade has revolutionized our understanding of the frequency of rocky exoplanets, showing that they are common (e.g., Quintana et al., 2014; Coughlin et al., 2016; Kane et al., 2016; Kane et al., 2019), close by (Gillon et al., 2016; Anglada-Escudé et al., 2016; Dittmann et al., 2017), and unique laboratories for understanding the processes that keep the Earth habitable (e.g., Checlair et al., 2018, Kane et al., 2014; Kane et al., 2019). Bounding the limits of habitability underpins what is likely the key motivation for observing these worlds: the search for life. In this vein, the community has outlined biosignatures ranging from atmospheric gases like O₂ and CH₄, spectroscopic identifications of biotic pigments such as the ‘red edge’, and even the ‘breathing’ of a biosphere in response to seasonal insolation changes (see, e.g., review in Schwieterman et al., 2018). But accompanying this is an evolving list of mechanisms that could mimic these biosignatures, which have been termed false positives, often with their own lists of discriminating features to make them separable from the biosignature. This means that not only must a planet be habitable and present detectable biosignatures, there must also be markers that diminish or rule out the possibility that there is an abiotic agent at work. Conventionally, this has been cast as a decision tree (e.g., the ‘champagne plot’ from Harman & Domagal-Goldman, 2018), but the signs of habitability and inhabitation form at once a pyramid (each factor building on the previous one) and a set of factors balanced against one another.

The balancing act of weighing habitability, biosignatures, and false positives requires specific language at each step, to help quantify uncertainty and the likelihood that a given scenario is most likely driven by life, as well as to identify specific areas for improvement where the clear resolution of statistical likelihood is obscured. A Bayesian approach works well to incorporate critical contextual information, and can include everything from parameters well-constrained by observations of the modern Earth, to factors that are not directly observable (Catling et al., 2018; Walker et al., 2018; see Fig. 1). This makes underlying assumptions about the strength of any given piece of evidence clear and allows for contextual information to add meaningful nuance to the interpretation of observations. Below, we outline terminology and key advances necessary to pursue the goal of detecting life in the face of these issues over the next decade and beyond.

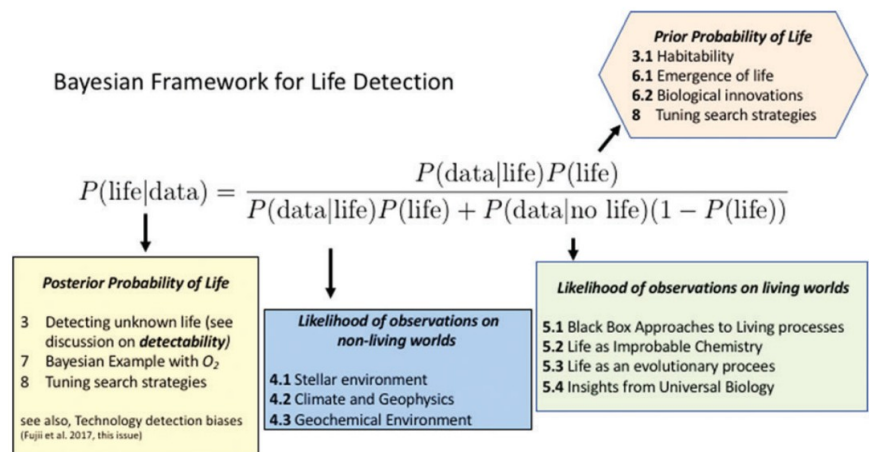


Fig. 1: Conceptual diagram of the Bayesian framework applied to biosignatures. Taken from Walker et al. (2018).

Habitability markers and precluders

Habitability markers provide direct or indirect evidence that a surface environment is conducive to supporting life. The most used criterion for exoplanet habitability is the capacity for stable surface liquid water (e.g., Kopparapu et al., 2013; 2016), which bounds the range of inso-

lations that should be targeted for follow-up observations (e.g., Deming et al., 2009; Morley et al., 2017). This criterion can be assessed directly by observing ocean glint (Williams and Gaidos 2008; Robinson et al. 2014) or indirectly by constraining temperature and pressure to be in the stability regime for liquid water. Detection of water vapor (H₂O), carbon dioxide (CO₂), and nitrogen (N₂) would contribute to this assessment. In addition to the narrow and specific requirement that a planetary surface be amenable to hosting liquid water, other surface conditions could be considered such as UV and particle irradiation, which at some intensities may destroy DNA (or other biomolecules), but at some level may be necessary for prebiotic chemistry to occur (Airapetian et al., 2016; Ranjan & Sasselov 2017; Rimmer et al. 2018).

A range of suggestions link the width of the habitable zone to host star type and semi-major axis (Kopparapu et al., 2013), planet mass and radius (Kopparapu et al., 2014), greenhouse gas inventories (e.g., Pierrehumbert and Gaidos, 2011; Abe et al., 2011; Kadoya and Tajika, 2014), and orbital parameters (e.g., Kane and Gelino, 2012), among others. Some of these will be constrained by or inferred from observations, opening the door to a more rigorous statistical approach (Apai et al., 2019). Often missing from these globally-forced estimates, however, is discussion connecting these partially- or super-habitable worlds (e.g., Dressing et al., 2010; Heller and Armstrong, 2014) to potential biospheres. This can range from biosphere size and productivity limitations driven by nutrient availability (Moore et al., 2013; Seager et al., 2013a; Bristow et al., 2017) or photon fluxes (Kiang et al., 2007a,b; Rugheimer et al., 2015; Lingam and Loeb, 2017; Lehmer et al., 2018) to implications for the type and strength of surface biosignatures (e.g., Grenfell et al., 2014). More directly linking gross habitability markers to biological necessities can then link habitability more strongly to biosignature production and detectability.

Contrasting this, direct or indirect evidence that the surface and near-surface environments are inhospitable to known or hypothetical forms of life precludes habitability. For example, UV surface irradiation beyond the limit for dissociating DNA (Rugheimer et al. 2015; O'Malley-James and Kaltenegger 2017), particularly if it is strong enough to dissociate DNA under water to depths beyond photosynthetic active region (PAR) viability (a concern for flaring M dwarfs), would contradict the more general habitability condition provided by liquid water. On the other hand, too little NUV radiation may reduce the availability of precursor molecules relevant to the origin of life (Ranjan & Sasselov, 2017; Ranjan et al., 2017; Rimmer et al., 2018). Other examples could include measured temperatures beyond viability limits for known extremophiles or the absence of water vapor, representing either a frozen or hot, desiccated world.

That said, habitability precluders may not necessarily imply uniformity on a global scale, as evinced by recent work on the nuances of habitability (Yang et al., 2014; Kopparapu et al., 2016; Haqq-Misra et al., 2016). It is then important to constrain what (if any) habitable niches may exist, and what their potential impact could be on atmospheric chemistry, to estimate the likelihood of biosignatures. Because of the overlap of known false positives with conventionally uninhabitable conditions (e.g., Luger and Barnes, 2015; Gao et al., 2015; Airapetian et al. 2017a), it is important to also connect habitability precluders with potential false positive scenarios.

Biosignatures and anti-biosignatures

Biosignatures have previously been defined as any “object, substance, and/or pattern whose origin specifically requires a biological agent” (Des Marais and Walter 1999; Des Marais et al. 2008). In the context of exoplanet biosignatures, where only remote information about a planet’s atmosphere and/or surface may be obtained, the classification of a biosignature will be

necessarily tentative, thus all remote biosignatures are potential biosignatures. We suggest endorsing the more general definition proposed by Catling et al. (2018): “a biosignature is any substance, group of substances, or phenomenon that provides evidence of life.” In a Bayesian framework, a biosignature is probabilistic evidence in favor of life, such as “an object, substance, and/or pattern that increases the likelihood that the signal is generated by life, such that $P(\text{data}|\text{life})$ is greater than in its absence (e.g., a piece of evidence B is a biosignature if $P(\text{data}|\text{life}, B) > P(\text{data}|\text{life})$ ” (see Catling et al., 2018; Walker et al., 2018).

Discoveries go both directions; what we learn from Earth’s past and present biosphere and what indelible marks it leaves on the Earth’s atmosphere can continue to inform biosignature searches in the future. Likewise, constraints on the likelihood of conditions conducive to the formation and evolution of life will narrow the focus for future origin-of-life studies. This also means that we work towards a better understanding of the biosignatures for a low- or no-oxygen atmosphere, requiring further exploration of novel biosignatures (Seager et al., 2013b; 2016), as well as more strongly linking habitability drivers to compatible chemical regimes and biosignatures. Biosignature studies have historically relied on 1-D photochemical and climate simulations, whereas clouds and hazes can be spatially and temporally heterogeneous (Fortney et al., 2019) and work to obfuscate any biosignatures. Mapping spectral biosignature retrievals using more complex models could result in more information about the same world (in the same vein as Cowan et al., 2009) and more closely match observations (e.g., Kataria et al., 2015).

An anti-biosignature, on the other hand, is often loosely defined as evidence of chemical free energy in the environment not exploited by life, but this definition is likely inadequate. A broader and more widely applicable definition of an anti-biosignature is given by Catling et al. (2018): “any substance, group of substances, or phenomenon that provides evidence against the presence of life.” Using a Bayesian framework, Walker et al. (2018) define an “anti-biosignature” as: “an object, substance, and/or pattern that diminishes the likelihood the signal is generated by life, such that $P(\text{data}|\text{life})$ is less than in its absence (e.g., a given piece of contextual information C is an anti-biosignature if $P(\text{data}|\text{life}, C) < P(\text{data}|\text{life})$). An equally valid conceptualization would be to define “C” as an anti-biosignature if $P(\text{data}|\text{no life}, C) > P(\text{data}|\text{no life})$. CO is particularly relevant as an anti-biosignature because as a reduced form of carbon relative to environmental CO₂ it is both a source of electrons and a source of carbon (Ragsdale 2004). In the case of exoplanet atmospheres, the classification of CO as an anti-biosignature is context-dependent: for inhabited, oxygen-rich planets orbiting Sun-like stars its concentration is likely to be very low, but could be substantially higher for planets orbiting M dwarf stars (Schwieterman et al., in press), or reducing atmospheres like the early Earth’s (Kharecha et al., 2005).

False positive markers and precluders

False positive markers provide spectroscopic evidence that abiotic processes are operating that can produce false positive biosignatures. Examples include CO, O₂, and CO₂ in abundance ratios suggestive of CO₂ photolysis or O₂ bands that suggest O₂ atmospheres too massive to be biologically produced, left behind by a history of robust H₂-escape (see, e.g., Schwieterman et al. 2016; Meadows 2017; Harman and Domagal-Goldman 2018; Meadows et al. 2018). (In the CO₂ photolysis scenario, it is possible CO could be both a false positive marker and an anti-biosignature, though this depends on context.) Crucially, false positive markers are not themselves necessarily anti-biosignatures, since life may exist despite other, non-related abiotic processes generating putative biosignatures. A false positive marker reduces the probability that tentative biosignatures were produced by life, but can only be weighed against the biosignature evi-

dence susceptible to the inferred false positive. In other words, confirming a false positive for photosynthetic O₂ does not necessarily rule out non-oxygen biosignatures. Thus, in a Bayesian sense, given a potential biosignature B and a possible false positive marker M, it must be true that $P(\text{data}|\text{life}, B) > P(\text{data}|\text{life}, B, M) \geq P(\text{data}|\text{life})$.

The recent evolution in known false positive mechanisms, especially for planets orbiting M dwarfs, should be a key area for future work. Recent advances have begun to characterize the high energy spectra of stars as a function of age and type (Shkolnik and Barman, 2014; France et al., 2016; Miles and Shkolnik, 2017; Youngblood et al., 2017; France et al., 2018) which will be necessary to bound false positives generated by atmospheric chemistry models. Further work is necessary to quantify variability and flares (Airapetian et al., 2017b; Loyd et al., 2018; Tilley et al., 2019), which potentially overlaps with concerns regarding habitability. From the Earth sciences, a better understanding of Earth's atmospheric nitrogen and oxygen evolution, driven by feedbacks between biology and geochemical sinks, can inform work related to the formation and preservation of abiotic O₂ (e.g., Wordsworth and Pierrehumbert, 2014; Harman et al., 2015). Lastly, improved constraints on critical reactions (e.g., He et al., 2018; Kao et al., 2019) and sink processes (e.g., Harman et al., 2015; Harman et al., 2018) can also limit or rule out some false positive scenarios.

Balanced against this, any spectroscopic evidence that rules out or renders less probable abiotic processes that could produce false positive biosignatures can be said to preclude that false positive. For example, a deficit of non-condensing gases could potentially favor the buildup of abiotic oxygen (Wordsworth and Pierrehumbert 2014; Wordsworth et al. 2017); however, the detection of sufficient non-condensing gases such as N₂ through N₂-N₂ spectroscopic features could preclude this scenario (Schwieterman et al. 2015); alternatively, Rayleigh scattering may constrain atmospheric mass to the extent that this scenario is ruled out (Meadows 2017; Meadows et al. 2018). In a Bayesian framework, given a biosignature B and evidence that makes that biosignature less likely to have been produced by abiotic processes, E, we have: $P(\text{data}|\text{life}, B, E) > P(\text{data}|\text{life}, B) > P(\text{data}|\text{life})$.

Researchers focused on identifying and quantifying false positive scenarios should be encouraged to go beyond simply reporting the issue, instead striving to include analyses of any potential precluders. Further, such modeling work should happen jointly with observation design such that we can be sure to capture false positive precluders when searching for habitability markers and biosignatures. Identifying additional precluders and/or faster and more reliable methods to retrieve precluder information for currently known false positive scenarios should be a top priority (e.g., Schwieterman et al., 2015).

Moving Forward

We reiterate our endorsement of the findings and recommendations published in the National Academy reports on Exoplanet Science Strategy and Astrobiology Strategy for the Search for Life in the Universe. We have provided further context and motivation for a clear and consistent framework to quantify the results of our search for remote biosignatures, which will allow us to go beyond qualitative interpretations to a more robust, quantitative evaluation of how likely we think those signals are to a direct marker for the presence of life. **In general, our confidence that putative biosignatures are in actuality produced by life will increase with more spectral information, making multi-wavelength characterization of potential habitable planets essential.** Additionally, understanding planet-star interactions and consequent atmospheric photochemistry is essential for contextualizing the origin of biologically relevant trace gases and

planetary habitability. This argues for support for simultaneous stellar and planet characterization and associated modeling efforts.

References

- Abe, Y., Abe-Ouchi, A., Sleep, N.H. and Zahnle, K.J., 2011. Habitable zone limits for dry planets. *Astrobiology*, 11(5), pp.443-460.
- Airapetian, V. S., Glocer, A., Gronoff G., E. Hébrard, E., Danchi, W. 2016, Prebiotic chemistry and atmospheric warming of early Earth by an active young Sun. *Nature Geoscience*, Vol 9, Issue 6, 452-255.
- Airapetian, V. S., Jackman, C. H., Mlynczak, M., Danchi, W., Hunt, L. 2017a. Atmospheric Beacons of Life from Exoplanets Around G and K Stars, *Nature Scientific Reports*, 7, 14141-14150.
- Airapetian, V.S., Glocer, A., Khazanov, G.V., Loyd, R.O.P., France, K., Sojka, J., Danchi, W.C. and Liemohn, M.W., 2017b. How hospitable are space weather affected habitable zones? The role of ion escape. *The Astrophysical Journal Letters*, 836(1), p.L3.
- Anglada-Escudé, G., Amado, P.J., Barnes, J., Berdiñas, Z.M., Butler, R.P., Coleman, G.A., de La Cueva, I., Dreizler, S., Endl, M., Giesers, B. and Jeffers, S.V., 2016. A terrestrial planet candidate in a temperate orbit around Proxima Centauri. *Nature*, 536(7617), p.437.
- Apai, D., et al., 2019. Planetary Habitability Informed by Planet Formation and Exoplanet Demographics. White paper to be submitted for the 2020 Decadal Survey by the National Academy of Sciences.
- Bristow, L.A., Mohr, W., Ahmerkamp, S. and Kuypers, M.M., 2017. Nutrients that limit growth in the ocean. *Current Biology*, 27(11), pp.R474-R478.
- Catling, D.C., Krissansen-Totton, J., Kiang, N.Y., Crisp, D., Robinson, T.D., DasSarma, S., Rushby, A.J., Del Genio, A., Bains, W. and Domagal-Goldman, S., 2018. Exoplanet biosignatures: a framework for their assessment. *Astrobiology*, 18(6), pp.709-738.
- Checlair, J., Abbot, D.S., Bean, J.L., Kempton, E.M.R., Robinson, T.D. and Webber, R., 2018. A statistical comparative planetology approach to test the habitable zone concept. *LPI Contributions*, 2065.
- Coughlin, J.L., Mullally, F., Thompson, S.E., Rowe, J.F., Burke, C.J., Latham, D.W., Batalha, N.M., Ofir, A., Quares, B.L., Henze, C.E. and Wolfgang, A., 2016. Planetary candidates observed by Kepler. VII. The first fully uniform catalog based on the entire 48-month data set (Q1–Q17 DR24). *The Astrophysical Journal Supplement Series*, 224(1), p.12.
- Cowan, N.B., Agol, E., Meadows, V.S., Robinson, T., Livengood, T.A., Deming, D., Lisse, C.M., A'Hearn, M.F., Wellnitz, D.D., Seager, S. and Charbonneau, D., 2009. Alien maps of an ocean-bearing world. *The Astrophysical Journal*, 700(2), p.915.
- Deming, D., Seager, S., Winn, J., Miller-Ricci, E., Clampin, M., Lindler, D., Greene, T., Charbonneau, D., Laughlin, G., Ricker, G. and Latham, D., 2009. Discovery and characterization of transiting super Earths using an all-sky transit survey and follow-up by the James Webb Space Telescope. *Publications of the Astronomical Society of the Pacific*, 121(883), p.952.
- Des Marais, D.J., Nuth III, J.A., Allamandola, L.J., Boss, A.P., Farmer, J.D., Hoehler, T.M., Jakosky, B.M., Meadows, V.S., Pohorille, A., Runnegar, B. and Spormann, A.M., 2008. The NASA astrobiology roadmap. *Astrobiology*, 8(4), pp.715-730.
- Des Marais, D.J. and Walter, M.R., 1999. Astrobiology: exploring the origins, evolution, and distribution of life in the universe. *Annual review of ecology and systematics*, 30(1), pp.397-420.
- De Wit, J., Wakeford, H.R., Lewis, N.K., Delrez, L., Gillon, M., Selsis, F., Leconte, J., Demory, B.O., Bolmont, E., Bourrier, V. and Burgasser, A.J., 2018. Atmospheric reconnaissance of the habitable-zone Earth-sized planets orbiting TRAPPIST-1. *Nature Astronomy*, 2(3), p.214.
- Dittmann, J.A., Irwin, J.M., Charbonneau, D., Bonfils, X., Astudillo-Defru, N., Haywood, R.D., Berta-Thompson, Z.K., Newton, E.R., Rodriguez, J.E., Winters, J.G. and Tan, T.G., 2017. A temperate rocky super-Earth transiting a nearby cool star. *Nature*, 544(7650), p.333.
- Dressing, C.D., Spiegel, D.S., Scharf, C.A., Menou, K. and Raymond, S.N., 2010. Habitable climates: the influence of eccentricity. *The Astrophysical Journal*, 721(2), p.1295.
- Fortney, J.J., et al., 2019. The Need for Laboratory Work and Ab Initio Simulations to Aid in The Understanding of Exoplanetary Atmospheres. White paper to be submitted for the 2020 Decadal Survey by the National Academy of Sciences.
- France, K., Arulanantham, N., Fossati, L., Lanza, A.F., Loyd, R.P., Redfield, S. and Schneider, P.C., 2018. Far-ultraviolet Activity Levels of F, G, K, and M Dwarf Exoplanet Host Stars. *The Astrophysical Journal Supplement Series*, 239(1), p.16.
- France, K., Loyd, R.P., Youngblood, A., Brown, A., Schneider, P.C., Hawley, S.L., Froning, C.S., Linsky, J.L., Roberge, A., Buccino, A.P. and Davenport, J.R., 2016. The MUSCLES treasury survey. I. Motivation and overview. *The Astrophysical Journal*, 820(2), p.89.

- Gao, P., Hu, R., Robinson, T.D., Li, C. and Yung, Y.L., 2015. Stability of CO₂ atmospheres on desiccated M dwarf exoplanets. *The Astrophysical Journal*, 806(2), p.249.
- Gillon, M., Triaud, A.H., Demory, B.O., Jehin, E., Agol, E., Deck, K.M., Lederer, S.M., De Wit, J., Burdanov, A., Ingalls, J.G. and Bolmont, E., 2017. Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1. *Nature*, 542(7642), p.456.
- Grenfell, J.L., Gebauer, S., Paris, P.V., Godolt, M. and Rauer, H., 2014. Sensitivity of biosignatures on Earth-like planets orbiting in the habitable zone of cool M-dwarf Stars to varying stellar UV radiation and surface biomass emissions. *Planetary and Space Science*, 98, pp.66-76.
- Harman, C.E. and Domagal-Goldman, S., 2018. Biosignature False Positives. In: *Handbook of Exoplanets*. Springer International Publishing, Cham, pp 1–22.
- Harman, C.E., Felton, R., Hu, R., Domagal-Goldman, S.D., Segura, A., Tian, F. and Kasting, J.F., 2018. Abiotic O₂ Levels on Planets around F, G, K, and M Stars: Effects of Lightning-produced Catalysts in Eliminating Oxygen False Positives. *The Astrophysical Journal*, 866(1), p.56.
- Harman, C.E., Schwieterman, E.W., Schottelkotte, J.C. and Kasting, J.F., 2015. Abiotic O₂ levels on planets around F, G, K, and M stars: possible false positives for life?. *The Astrophysical Journal*, 812(2), p.137.
- Haqq-Misra, J., Kopparapu, R.K., Batalha, N.E., Harman, C.E. and Kasting, J.F., 2016. Limit cycles can reduce the width of the habitable zone. *The Astrophysical Journal*, 827(2), p.120.
- He, C., Hörst, S.M., Lewis, N.K., Moses, J.I., Kempton, E.M.R., Marley, M.S., Morley, C.V., Valenti, J.A. and Vuitton, V., 2018. Gas Phase Chemistry of Cool Exoplanet Atmospheres: Insight from Laboratory Simulations. *ACS Earth and Space Chemistry*.
- Heller, R. and Armstrong, J., 2014. Superhabitable worlds. *Astrobiology*, 14(1), pp.50-66.
- Kadoya, S. and Tajika, E., 2014. Conditions for oceans on Earth-like planets orbiting within the habitable zone: importance of volcanic CO₂ degassing. *The Astrophysical Journal*, 790(2), p.107.
- Kane, S.R., et al., 2019. Venus as a Nearby Exoplanet Laboratory. White paper to be submitted for the 2020 Decadal Survey by the National Academy of Sciences.
- Kane, S.R. and Gelino, D.M., 2012. The habitable zone and extreme planetary orbits. *Astrobiology*, 12(10), pp.940-945.
- Kane, S.R., Hill, M.L., Kasting, J.F., Kopparapu, R.K., Quintana, E.V., Barclay, T., Batalha, N.M., Borucki, W.J., Ciardi, D.R., Haghighipour, N. and Hinkel, N.R., 2016. A catalog of Kepler habitable zone exoplanet candidates. *The Astrophysical Journal*, 830(1), p.1.
- Kane, S.R., Kopparapu, R.K. and Domagal-Goldman, S.D., 2014. On the frequency of potential Venus analogs from Kepler data. *The Astrophysical Journal Letters*, 794(1), p.L5.
- Kao, D., et al., 2019. Impacts of Quantum Chemistry Calculations on Exoplanetary Science, Planetary Astronomy, and Astrophysics. White paper to be submitted for the 2020 Decadal Survey by the National Academy of Sciences.
- Kataria, T., Showman, A.P., Fortney, J.J., Stevenson, K.B., Line, M.R., Kreidberg, L., Bean, J.L. and Désert, J.M., 2015. The atmospheric circulation of the hot jupiter WASP-43b: Comparing three-dimensional models to spectrophotometric data. *The Astrophysical Journal*, 801(2), p.86.
- Kharecha, P., Kasting, J. and Siefert, J., 2005. A coupled atmosphere–ecosystem model of the early Archean Earth. *Geobiology*, 3(2), pp.53-76.
- Kiang, N.Y., Segura, A., Tinetti, G., Blankenship, R.E., Cohen, M., Siefert, J., Crisp, D. and Meadows, V.S., 2007a. Spectral signatures of photosynthesis. II. Coevolution with other stars and the atmosphere on extrasolar worlds. *Astrobiology*, 7(1), pp.252-274.
- Kiang, N.Y., Siefert, J. and Blankenship, R.E., 2007b. Spectral signatures of photosynthesis. I. Review of Earth organisms. *Astrobiology*, 7(1), pp.222-251.
- Kopparapu, R.K., Ramirez, R., Kasting, J.F., Eymet, V., Robinson, T.D., Mahadevan, S., Terrien, R.C., Domagal-Goldman, S., Meadows, V. and Deshpande, R., 2013. Habitable zones around main-sequence stars: new estimates. *The Astrophysical Journal*, 765(2), p.131.
- Kopparapu, R.K., Ramirez, R.M., Schottelkotte, J., Kasting, J.F., Domagal-Goldman, S. and Eymet, V., 2014. Habitable zones around main-sequence stars: dependence on planetary mass. *The Astrophysical Journal Letters*, 787(2), p.L29.
- Kopparapu, R., Wolf, E.T., Haqq-Misra, J., Yang, J., Kasting, J.F., Meadows, V., Terrien, R. and Mahadevan, S., 2016. The inner edge of the habitable zone for synchronously rotating planets around low-mass stars using general circulation models. *The Astrophysical Journal*, 819(1), p.84.
- Lehmer, O.R., Catling, D.C., Parenteau, M.N. and Hoehler, T.M., 2018. The productivity of oxygenic photosynthesis around cool, M dwarf stars. *The Astrophysical Journal*, 859(2), p.171.

- Lingam, M. and Loeb, A., 2017. Risks for life on habitable planets from superflares of their host stars. *The Astrophysical Journal*, 848(1), p.41.
- Lloyd, R.P., France, K., Youngblood, A., Schneider, C., Brown, A., Hu, R., Segura, A., Linsky, J., Redfield, S., Tian, F. and Rugheimer, S., 2018. The MUSCLES Treasury Survey. V. FUV Flares on Active and Inactive M Dwarfs. *The Astrophysical Journal*, 867(1), p.71.
- Luger, R. and Barnes, R., 2015. Extreme water loss and abiotic O₂ buildup on planets throughout the habitable zones of M dwarfs. *Astrobiology*, 15(2), pp.119-143.
- Meadows, V.S., 2017. Reflections on O₂ as a biosignature in exoplanetary atmospheres. *Astrobiology*, 17(10), pp.1022-1052.
- Meadows, V.S., Reinhard, C.T., Arney, G.N., Parenteau, M.N., Schwieterman, E.W., Domagal-Goldman, S.D., Lincowski, A.P., Stapelfeldt, K.R., Rauer, H., DasSarma, S. and Hegde, S., 2018. Exoplanet biosignatures: understanding oxygen as a biosignature in the context of its environment. *Astrobiology*, 18(6), pp.630-662.
- Miles, B.E. and Shkolnik, E.L., 2017. HAZMAT. II. Ultraviolet Variability of Low-mass Stars in the GALEX Archive. *The Astronomical Journal*, 154(2), p.67.
- Moore, C.M., Mills, M.M., Arrigo, K.R., Berman-Frank, I., Bopp, L., Boyd, P.W., Galbraith, E.D., Geider, R.J., Guieu, C., Jaccard, S.L. and Jickells, T.D., 2013. Processes and patterns of oceanic nutrient limitation. *Nature Geoscience*, 6(9), p.701.
- Morley, C.V., Kreidberg, L., Rustamkulov, Z., Robinson, T. and Fortney, J.J., 2017. Observing the atmospheres of known temperate Earth-sized planets with JWST. *The Astrophysical Journal*, 850(2), p.121.
- O'Malley-James, J.T. and Kaltenegger, L., 2017. UV surface habitability of the TRAPPIST-1 system. *Monthly Notices of the Royal Astronomical Society: Letters*, 469(1), pp.L26-L30.
- Pierrehumbert, R. and Gaidos, E., 2011. Hydrogen greenhouse planets beyond the habitable zone. *The Astrophysical Journal Letters*, 734(1), p.L13.
- Quintana, E.V., Barclay, T., Raymond, S.N., Rowe, J.F., Bolmont, E., Caldwell, D.A., Howell, S.B., Kane, S.R., Huber, D., Crepp, J.R. and Lissauer, J.J., 2014. An Earth-sized planet in the habitable zone of a cool star. *Science*, 344(6181), pp.277-280.
- Ragsdale, S.W., 2004. Life with carbon monoxide. *Critical reviews in biochemistry and molecular biology*, 39(3), pp.165-195.
- Ranjan, S. and Sasselov, D.D., 2017. Constraints on the early terrestrial surface UV environment relevant to prebiotic chemistry. *Astrobiology*, 17(3), pp.169-204.
- Ranjan, S., Wordsworth, R. and Sasselov, D.D., 2017. The surface UV environment on planets orbiting M dwarfs: implications for prebiotic chemistry and the need for experimental follow-up. *The Astrophysical Journal*, 843(2), p.110.
- Rimmer, P. B., Xu, J., Thompson, S. J., Gillen, E., Sutherland, J. D., and Queloz, D., 2018. The origin of RNA precursors on exoplanets. *Science Advances*, 4(8), eaar3302.
- Robinson, T.D., Ennico, K., Meadows, V.S., Sparks, W., Bussey, D.B.J., Schwieterman, E.W. and Breiner, J., 2014. Detection of ocean glint and ozone absorption using LCROSS Earth observations. *The Astrophysical Journal*, 787(2), p.171.
- Rugheimer, S., Segura, A., Kaltenegger, L. and Sasselov, D., 2015. UV surface environment of Earth-like planets orbiting FGKM stars through geological evolution. *The Astrophysical Journal*, 806(1), p.137.
- Schwieterman, E.W., Kiang, N.Y., Parenteau, M.N., Harman, C.E., DasSarma, S., Fisher, T.M., Arney, G.N., Harnett, H.E., Reinhard, C.T., Olson, S.L. and Meadows, V.S., 2018. Exoplanet biosignatures: a review of remotely detectable signs of life. *Astrobiology*, 18(6), pp.663-708.
- Schwieterman, E.W., Meadows, V.S., Domagal-Goldman, S.D., Deming, D., Arney, G.N., Luger, R., Harman, C.E., Misra, A. and Barnes, R., 2016. Identifying planetary biosignature impostors: spectral features of CO and O₂ resulting from abiotic O₂/O₃ production. *The Astrophysical Journal Letters*, 819(1), p.L13.
- Schwieterman, E.W., Reinhard, C.T., Olson, S.L., Ozaki, K., Harman, C.E., Hong, P.K., Lyons, T.W., in press. Rethinking CO antibiosignatures in the search for life beyond the solar system. *The Astrophysical Journal*.
- Schwieterman, E.W., Robinson, T.D., Meadows, V.S., Misra, A. and Domagal-Goldman, S., 2015. Detecting and constraining N₂ abundances in planetary atmospheres using collisional pairs. *The Astrophysical Journal*, 810(1), p.57.
- Seager, S., Bains, W. and Hu, R., 2013a. A biomass-based model to estimate the plausibility of exoplanet biosignature gases. *The Astrophysical Journal*, 775(2), p.104.
- Seager, S., Bains, W. and Hu, R., 2013b. Biosignature gases in H₂-dominated atmospheres on rocky exoplanets. *The Astrophysical Journal*, 777(2), p.95.

- Seager, S., Bains, W. and Petkowski, J.J., 2016. Toward a list of molecules as potential biosignature gases for the search for life on exoplanets and applications to terrestrial biochemistry. *Astrobiology*, 16(6), pp.465-485.
- Shkolnik, E.L. and Barman, T.S., 2014. HAZMAT. I. The evolution of far-UV and near-UV emission from early M stars. *The Astronomical Journal*, 148(4), p.64.
- Tilley, M.A., Segura, A., Meadows, V., Hawley, S. and Davenport, J., 2019. Modeling Repeated M Dwarf Flaring at an Earth-like Planet in the Habitable Zone: Atmospheric Effects for an Unmagnetized Planet. *Astrobiology*, 19(1), pp.64-86.
- Walker, S.I., Bains, W., Cronin, L., DasSarma, S., Danielache, S., Domagal-Goldman, S., Kacar, B., Kiang, N.Y., Lenardic, A., Reinhard, C.T. and Moore, W., 2018. Exoplanet biosignatures: future directions. *Astrobiology*, 18(6), pp.779-824.
- Williams, D.M. and Gaidos, E., 2008. Detecting the glint of starlight on the oceans of distant planets. *Icarus*, 195(2), pp.927-937.
- Wordsworth, R. and Pierrehumbert, R., 2014. Abiotic oxygen-dominated atmospheres on terrestrial habitable zone planets. *The Astrophysical Journal Letters*, 785(2), p.L20.
- Wordsworth, R.D., Schaefer, L.K. and Fischer, R.A., 2018. Redox evolution via gravitational differentiation on low-mass planets: Implications for abiotic oxygen, water loss, and habitability. *The Astronomical Journal*, 155(5), p.195.
- Yang, J., Boué, G., Fabrycky, D.C. and Abbot, D.S., 2014. Strong dependence of the inner edge of the habitable zone on planetary rotation rate. *The Astrophysical Journal Letters*, 787(1), p.L2.
- Youngblood, A., France, K., Loyd, R.P., Brown, A., Mason, J.P., Schneider, P.C., Tilley, M.A., Berta-Thompson, Z.K., Buccino, A., Froning, C.S. and Hawley, S.L., 2017. The MUSCLES Treasury Survey. IV. Scaling relations for ultraviolet, Ca II K, and energetic particle fluxes from M dwarfs. *The Astrophysical Journal*, 843(1), p.31.