2017 NAI Annual Science Report

Reporting Period: January 1, 2017 – December 31, 2017

Name: Edward Schwieterman

Team: Alternative Earths

Advisor: Dr. Timothy Lyons

Project Title: Visualizing Alternative Earths Through Time and Space

Accomplishments

As outlined in my NPP proposal, my research efforts in my first year have focused on leveraging knowledge about Earth's atmospheric and surface evolution through time to inform our expectations of the spectral character of habitable and inhabited exoplanets. I have contributed to several papers since the start of my appointment that align with this theme. Notably, one of these studies (Reinhard et al., 2017) combines results from geochemical proxies, biogeochemical modeling, and spectral modeling to specifically explore the detectability of potential remote biosignatures O_2, O_3, and CH_4 through Earth history. We find that significant portions of Earth history may be 'false negative' windows for detecting Earth's biosphere, at least through the O_2-CH_4 disequilibrium couple, pushing us to develop more robust and general frameworks for exoplanet biosignature analysis. Other conclusions from the paper include specific recommendations applicable to instrument design for future space-based telescopes capable of characterizing nearby habitable zone planets; specifically, an emphasis on the UV Hartley-Huggins O_3 band (~0.25 um), which may be observable even at very low O_2 levels now believed possible for Earth's mid-Proterozoic period (pO_2 ~ 0.1% PAL).

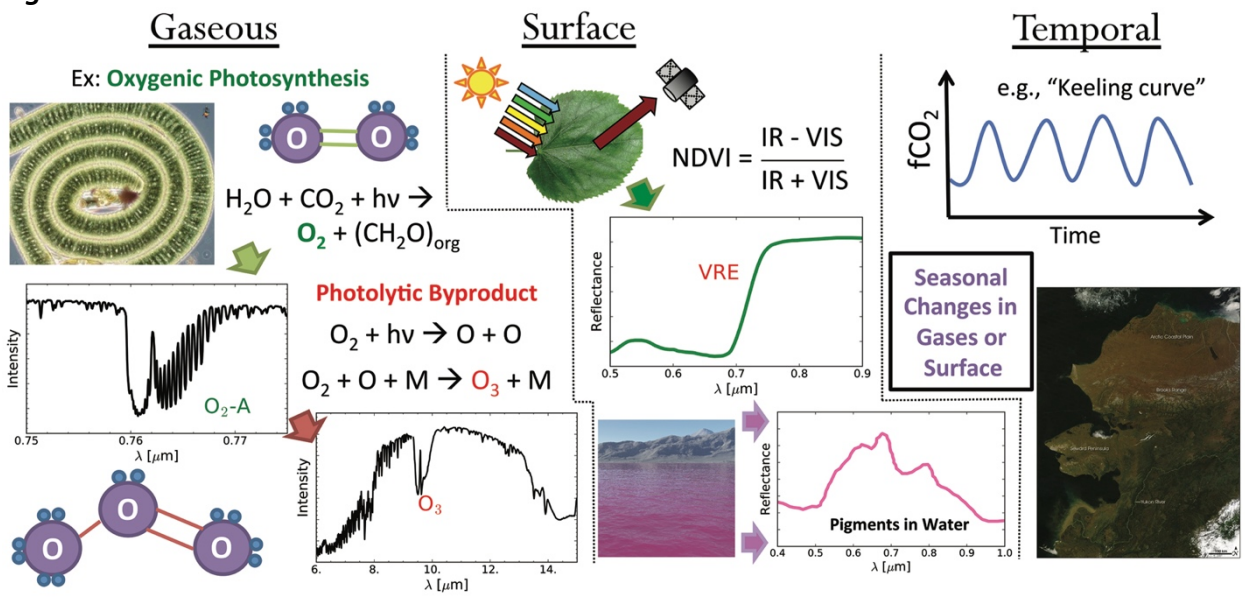
In addition, I led a robust review of exoplanet biosignature work to date, which evolved out of conversations held the NASA Nexus for Exoplanet System Science (NExSS) Exoplanet Biosignature Workshop Without Walls (EBWW) in summer 2016. This review not only summarizes the state of the field of exoplanet biosignatures, but draws new connections between topics to reach novel conclusions about biosignature strategies, and brings forward specialist literature not typically examined in the context of remote biosignatures to make recommendations for future work. Contained within this review is aggregated knowledge about each biosignature gas and surface feature relevant to early Earth and potentially exoplanets, including each one outlined in my NPP proposal, which will serve as a foundation for future examination in my continuing research. This paper was accepted by Astrobiology in December 2017 and will be published in May 2018.

To summarize by the numbers, in 2017 had one first-author paper accepted, authored a book chapter that has been published, co-authored five published or in press papers, co-authored an additional book chapter that has been published, led three extended abstracts at scientific

conferences, and contributed to a further 10 extended abstracts at scientific conferences. I also co-organized and co-chaired an oral session at the Astrobiology Science Conference.

Figures (1-4 each dominated one page below)

Figure 1

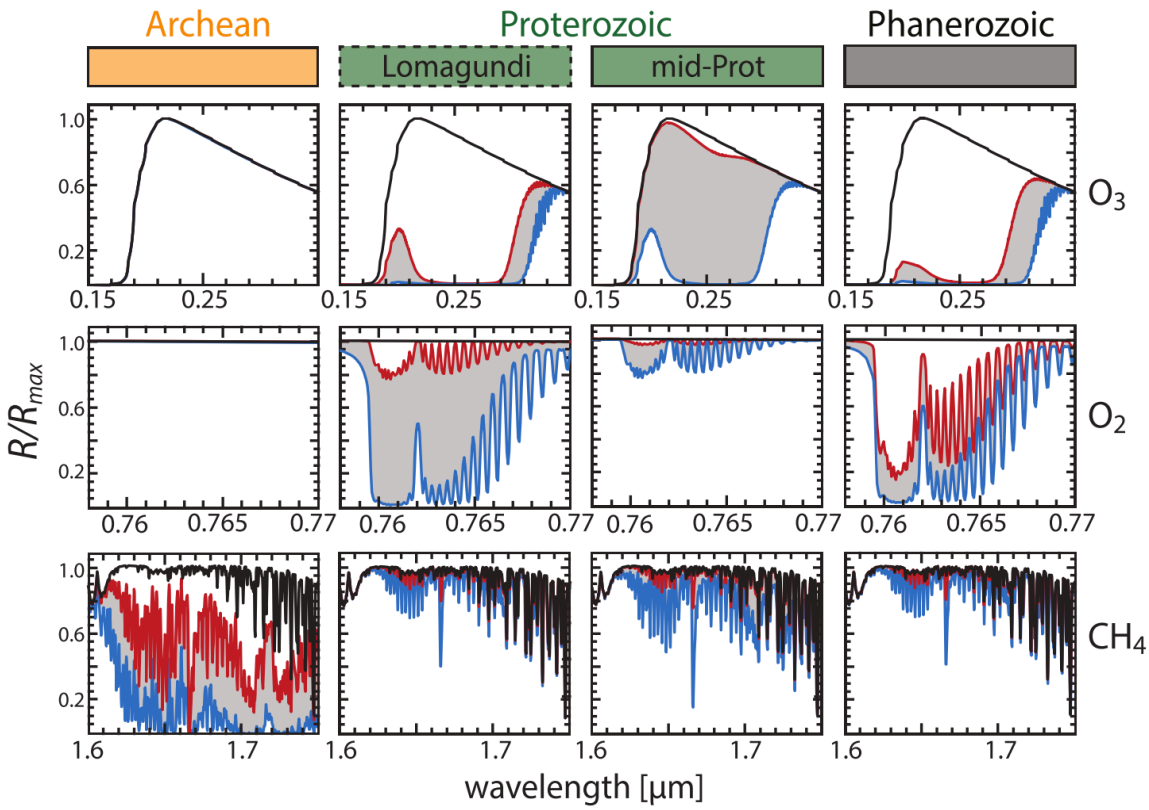


Alt-text: Summary of gaseous, surface, and temporal biosignatures in Schwieterman et al. 2018 review in *Astrobiology.*

Credit: E. Schwieterman. **Schwieterman, E.W.** et al. 2018. Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life. *Astrobiology*, in press. arXiv preprint 1705.05791

Caption: Summary of gaseous, surface, and temporal biosignatures. *Left panel:* gaseous biosignatures are direct or indirect products of biological processes. One example is molecular oxygen (O_2) generated as a byproduct of photosynthesis that is photochemically processed into ozone (O_3) in the stratosphere. *Middle panel:* surface biosignatures are the spectral signatures imparted by reflected light that interacts directly with living material. One example is the well-known vegetation "red edge" (VRE) produced by plants and the associated Normalized Difference Vegetation Index (NDVI) used for mapping surface vegetation on Earth (Tucker, 1979). *Right panel*: time-dependent changes in observable quantities, including gas concentrations or surface albedo features, may represent a temporal biosignature if they can be linked to the response of a biosphere to a seasonal or diurnal change. An example is the seasonal oscillation of CO_2 as a response to the seasonal growth and decay of vegetation (e.g., Keeling, 1976). This figure is reproduced with permission from Schwieterman (2016). Sub-image credits: NASA and the Encyclopedia of Life (EOL). (Caption text from Schwieterman et al. 2018.)

Figure 2

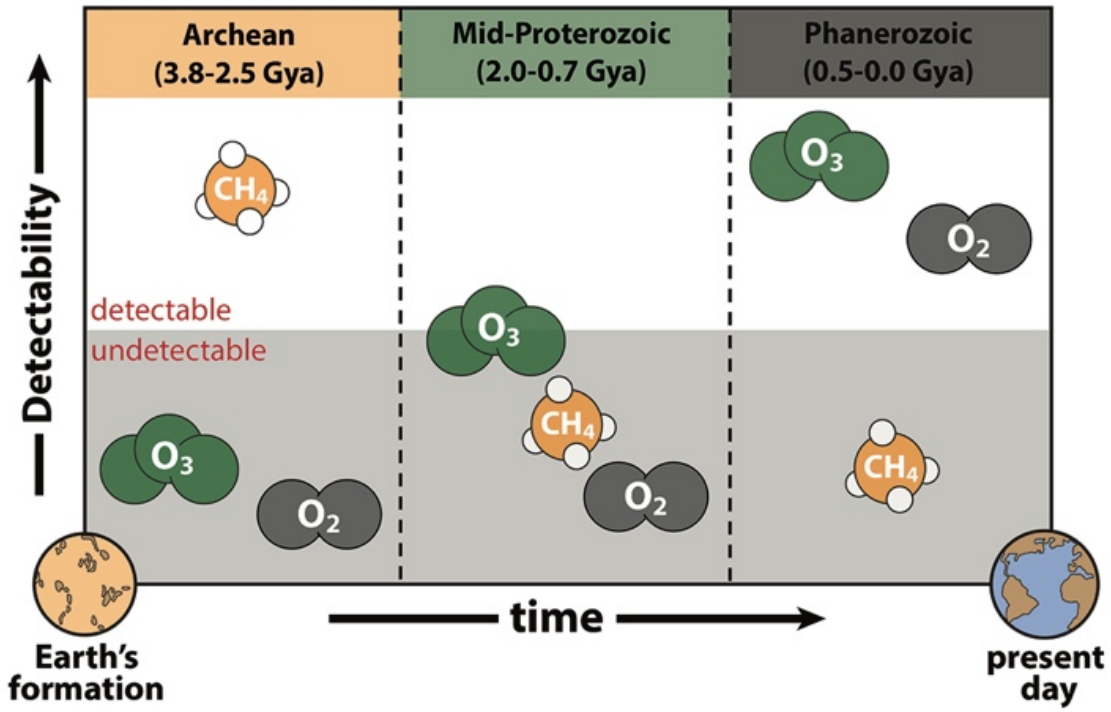


Alt-Text: Reflectance spectra of selected O_2, O_3, and CH_4 bands as a function of geologic epoch.

Credit: E. Schwieterman. Reinhard, C.T., Olson, S.L., **Schwieterman, E.W.**, Lyons, T.W., 2017. False Negatives for Remote Life Detection on Ocean-Bearing Planets: Lessons from the Early Earth. Astrobiology 17, 287–297.

Caption: Reflectance spectra of selected O_2, O_3, and CH_4 bands as a function of geologic epoch. Lower abundance limits are given in red, upper limits are given in blue, and the region between these limits is shaded grey. The black line represents the case with no absorption of O_2, O_3, or CH_4. Limits are representative of both uncertainties in atmospheric abundance and the variability of those abundances over the course of each epoch (Table 1). Values for peak atmospheric O_3 are calculated as a function of ground-level pO_2 according to the results of Kasting and Donahue (1980). The resolution of each spectrum is 1 cm-1, which is approximately $\Delta\lambda = 6.25 \times 10^{-6}$ μm at 0.25 μm, $\Delta\lambda = 5.78 \times 10^{-5}$ μm at 0.76 μm, and $\Delta\lambda = 2.72 \times 10^{-4}$ μm at 1.65 μm. We used a solar zenith angle of 60º to approximate a disk- average. Note that reflectances are arbitrarily scaled to provide a qualitative assessment of potential detectability. (Caption Text from Reinhard et al. 2017.)

Figure 3

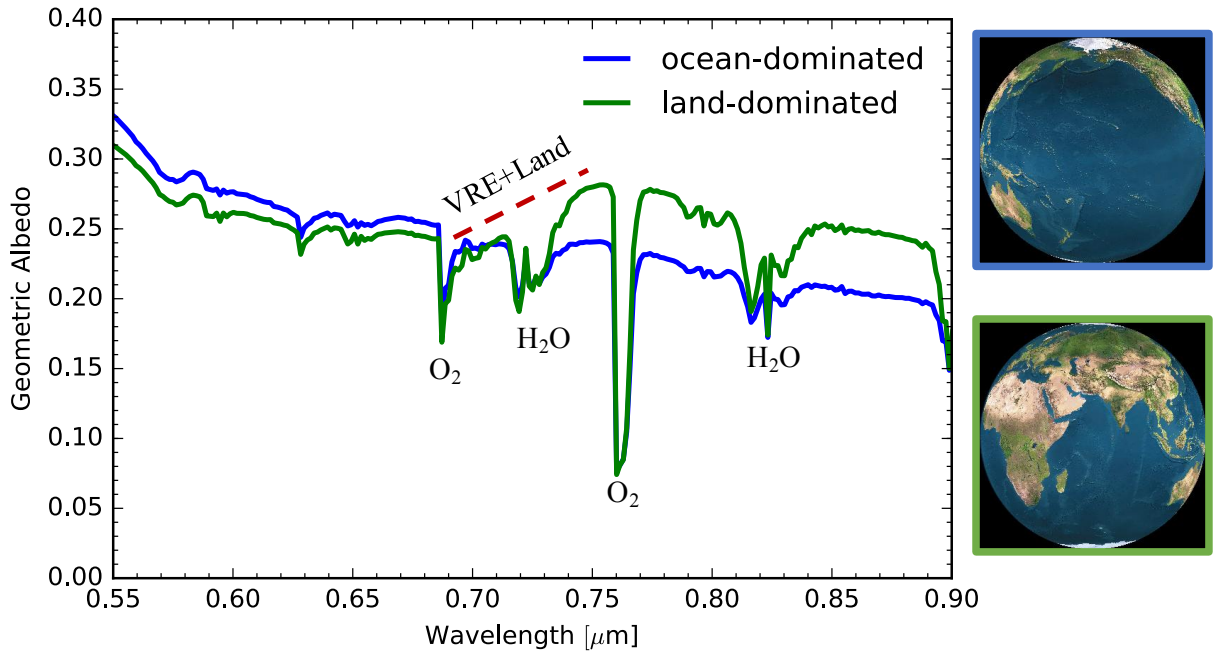


Alt-Text: Concept figure illustrating potential "false negatives" for remote life detection.

Credit: Schwieterman, E.W. et al. 2018. Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life. *Astrobiology*, in press. arXiv preprint 1705.05791

Caption: Conceptual figure illustrating the difficulty of detecting the O_2-CH_4 disequilibrium signature through Earth history. Note that the three columns in this figure correspond directly to the first, third, and fourth columns in Figure 2 above. (Caption text from Schwieterman et al., 2018).

Figure 4



Alt-Text: The red-edge in synthetic disk-averaged Earth model spectra.

Credit: E. Schwieterman. **Schwieterman E.W.** (2018) Surface and Temporal Biosignatures. In: Deeg H., Belmonte J. (eds) Handbook of Exoplanets. Springer, Cham. doi: 10.1007/978-3-319-30648-3_69-1

Caption: Synthetic disk-averaged spectra of Earth at ocean (blue) and land-dominated (green) views (consistent with Lunar viewing angles) produced using the Virtual Planetary Laboratory's 3D spectral Earth model described in Robinson et al. (2011). The increase in albedo between 0.7 and 0.75 μm is partially caused by the VRE in addition to the brightness of soil at these wavelengths (see composite surface albedos in Figure 1, left panel). Note that a water band at ~0.72 μm partially confounds the VRE signal. The images to the right show the distribution of land and ocean at the ocean and land-dominated views and were created using the Earth and Moon Viewer (http://www.fourmilab.ch/earthview).

Collaborations (please provide names and institutions):

Collaboration with other individuals and teams within and outside the NAI has been essential to my work and provided valuable contributions to others. Besides researchers within the NAI Alternative Earths team where I am based, I have most closely and fruitfully collaborated with members of the NAI Virtual Planetary Laboratory and the LUVOIR Science and Technology Definition Team (STDT) based at NASA Goddard Space Flight Center. I have also collaborated with members of the Blue Marble Space Institute of Science and others through the NExSS Exoplanet Biosignatures Workshop Without Walls. I have listed a subset of the individuals I have collaborated with below. The results of these collaborations include published manuscripts, white papers, book chapters, and conference presentations.

Collaborators:
Stephanie Olson, University of California Riverside (NAI Alternative Earths)
Timothy Lyons (supervisor), University of California, Riverside (NAI Alternative Earths)
Christopher Reinhard, Georgia Institute of Technology, Atlanta (NAI Alternative Earths)
Victoria Meadows, University of Washington, Seattle (NAI Virtual Planetary Laboratory)
Giada Arney, NASA Goddard Space Flight Center (NAI Virtual Planetary Laboratory; LUVOIR)
Shawn Domagal-Goldman, NASA Goddard (NAI Virtual Planetary Laboratory; LUVOIR team)
Mary N. Parenteau, NASA Ames Researcher Center (NAI Virtual Planetary Laboratory)
Nancy Y. Kiang, NASA GISS (NAI Virtual Planetary Laboratory)
Sara I. Walker, Arizona State University (Blue Marble Space Institute of Science)
Jacob Haqq-Misra, Blue Marble Space Institute of Science
Shiladitya DasSarma, University of Maryland (NExSS workshop participant)

Field Sites
Not applicable.

Field Site Images
Not applicable.

Publications/Presentations

Peer Reviewed Journal Articles (NAI support acknowledged):

Schwieterman, E.W. et al. 2018. Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life. *Astrobiology*, in press. arXiv preprint 1705.05791 [accepted December 2017]

Reinhard, C.T., Olson, S.L., **Schwieterman, E.W.**, Lyons, T.W., 2017. False Negatives for Remote Life Detection on Ocean-Bearing Planets: Lessons from the Early Earth. Astrobiology 17, 287–297.

Meadows, V.S., Reinhard, C.T., Arney, G.N., Parenteau, M.N., **Schwieterman, E.W.** et al**.**, 2018. Exoplanet Biosignatures: Understanding Oxygen as a Biosignature in the Context of Its Environment. Astrobiology, in press. arXiv preprint 1705.07560 [accepted December 2017]

Walker, S.I., et al. (including **Schwieterman, E.W.**) 2018. Exoplanet Biosignatures: Future Directions. *Astrobiology*, accepted. arXiv preprint 1705.08071 [accepted December 2017]

Meadows, V.S., Arney, G.N., **Schwieterman, E.W.** et al. 2018. The Habitability of Proxima Centauri b: Environmental States and Observational Discriminants *Astrobiology*, 18(2). doi: 10.1089/ast.2016.1589 [accepted in 2017]

Arney, G.N., et al. (including **Schwieterman, E.**) 2017. Pale Orange Dots: The Impact of Organic Haze on the Habitability and Detectability of Earthlike Exoplanets. *The Astrophysical Journal* 836, 49.

Book Chapters (NAI support acknowledged):

Schwieterman E.W. (2018) Surface and Temporal Biosignatures. In: Deeg H., Belmonte J. (eds) Handbook of Exoplanets. Springer, Cham. doi: 10.1007/978-3-319-30648-3_69-1 [accepted in 2017]

Olson S.L., **Schwieterman E.W.,** Reinhard C.T., Lyons T.W. (2018) Earth: Atmospheric Evolution of a Habitable Planet. In: Deeg H., Belmonte J. (eds) Handbook of Exoplanets. Springer, Cham. doi: 10.1007/978-3-319-30648-3_189-1 [accepted in 2017]

Extended Abstracts/Presentations (NAI affiliation noted):

Extended Abstracts Primary Presenter:

- **Schwieterman, E.W.,** Lustig-Yaeger, J., Meadows, V.S., Robinson, T.D., Sparks, W.B. A Phase-dependent Spectral Earth Database With Applications For Directly Imaged Earth-like Exoplanets. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3515. (April 2017) [LINK]

- **Schwieterman, E.W.,** Olson, S.L., Reinhard, C.T, Meadows, V.S., Lyons, T.W. Evaluating N2O as an Exoplanet Biosignature: Combining Biogeochemical, Photochemical, and Spectral Models. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id.3487. (April 2017) [LINK]

- **Schwieterman, E.,** Olson, S., Reinhard, C., Meadows, V., Lyons, T. Characterizing N2O as an Exoplanet Biosignature: Early Earth as a Template. Goldschmidt conference, held in Paris, France, Aug 12-18, 2017. (August 2017) [LINK]

Extended Abstracts Co-author presenter:

- Harman, C.E., **Schwieterman, E.W.,** Schottelkotte, J. C., and Kasting, J. F. Oxygen False Positives in Terrestrial Planetary Atmospheres: Taking a Closer Look at Proxima Centauri b. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3605. (April 2017) [LINK]

- Lustig-Yaeger, J., Tovar, G., Fujii, Y., **Schwieterman, E.W**., and Meadows, V.S. Mapping Surfaces and Clouds on Terrestrial Exoplanets Observed with Next-generation Coronagraph-equipped Telescopes. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3558. (April 2017) [LINK]

- Reinhard, C.T., Olson, S.L., **Schwieterman, E.W.,** Lyons, T.W. False Negatives for Remote Life Detection on Ocean-bearing Planets: Lessons From the Early Earth. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3451. (April 2017) [LINK]

- Meadows, V.S., Arney, G.N., **Schwieterman, E.W.,** Lustig-Yaeger, J., Lincowski, A.P., Robinson, T., Domagal-Goldman, S.D., Barnes, R.K., Fleming, D.P., Deitrick, R., Luger, R., Driscoll, P.E., Quinn, T.R., Crisp, D. Proxima Centauri B: Environmental States and Observational Discriminants. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3615. (April 2017) [LINK]

- Fleming, D.P., Barnes, R., Deitrick, R., Luger, R., Driscoll, P.E., Quinn, T.R., Guyer, B., McDonald, D. V., Meadows, V.S., Arney, G., Crisp, D., Domagal-Goldman, S.D., Lincowski, A., Lustig-Yaeger, J., **Schwieterman, E.** Coupled Atmospheric-Ocean-Tidal Evolution of Proxima Centauri b. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3383. (April 2017) [LINK]

- Deitrick, R., Quinn, T., Barnes, R., Kaib, N., Luger, R., Driscoll, P.E., Fleming, D.P., Guyer, B., MacDonald, D.V., Meadows, V.S., Arney, G., Crisp, D., Domagal-Goldman, S.G., Lincowski, A., LustigYaeger, J., **Schwieterman, E.** Death Stars: How Alpha Centauri Threatens Proxima's Planetary System. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3441. (April 2017) [LINK]

- Luger, R., Barnes, R., Deitrick, R., P. E. Driscoll, P.E., Quinn, T.R., Fleming, D.P., Guyer, B., McDonald, D. V., Meadows, V.S., Arney, G., Crisp, D., Domagal-Goldman, S.D., Lincowski, A., Lustig-Yaeger, J., **Schwieterman, E.** Evolution of the Water Content of Proxima Centauri b. The Astrobiology Science Conference 2017, held April 24–28, 2017 in Mesa, Arizona. No. 1965, id. 3534. (April 2017) [LINK]

- Kasting, J.F., Harman, C.E., **Schwieterman, E.W.** Understanding Remote Biosignatures Using Earth's Atmospheric Evolution as a Template. Goldschmidt conference, held in Paris France, Aug 12-18, 2017. [LINK]

- Stueken, E.E., Kipp, M.A., Koehler, M.C., **Schwieterman, E.W.,** Johnson, B., Buick, R. Nitrogen in minerals and atmospheres – a sign of life? Goldschmidt conference, held in Paris France, Aug 12-18, 2017. [LINK]

- Olson, S., **Schwieterman, E.,** Reinhard, C., Lyons, T. Atmospheric Seasonality on Early Earth: Implications for Remote Detection. Goldschmidt conference, held in Paris France, Aug 12-18, 2017. [LINK]

Flight Mission Involvement

Yes, I am involved in contributing materials to the NASA LUVOIR (Large Ultraviolet-Optical-Infrared Telescope) Science and Technology Definition Team (STDT). I am a coauthor on the interim report which is being prepared for release in 2018.

Mission Name: LUVOIR Science and Technology Definition Team (STDT)
Team Member(s): Edward Schwieterman
How are they involved: Providing spectral calculations and report materials including figures, figure captions, and text.

Astrobiology Strategy 2015 Objectives
(Relevant Objectives highlighted)

Topic 4 - CO-EVOLUTION OF LIFE AND THE PHYSICAL ENVIRONMENT

- ❑ I. How Does the Story of Earth—Its Past, Present, and Future—Inform Us about How the Climates, Atmospheric Compositions, Interiors, and Biospheres of Planets Can Co-Evolve?

Topic 5 - IDENTIFYING, EXPLORING, AND CHARACTERIZING ENVIRONMENTS FOR HABITABILITY AND BIOSIGNATURES

- ❑ II. How Can We Enhance the Utility of Biosignatures to Search for Life in the Solar System and Beyond?
- ❑ III. How Can We Identify Habitable Environments and Search for Life within the Solar System?
- ❑ IV. How Can We Identify Habitable Planets and Search for Life beyond the Solar System?

Topic 6 - CONSTRUCTING HABITABLE WORLDS

- ❑ V. How Does Habitability Change Through Time?