

THE TOPOLOGY OF ATMOSPHERIC CHEMICAL REACTION NETWORKS: A POTENTIAL NEW BIOSIGNATURE FOR EXOPLANETS.

T. M. Fisher¹, S. I. Walker², H. Smith³, M. Line⁴, J. Lyons⁵, and C. Ruiz⁶
¹ ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, tfisher4@asu.edu, ² ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, sara.i.walker@asu.edu, ³ ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, hbs@asu.edu, ⁴ ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, mrline@asu.edu, ⁵ ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, jimlyons@asu.edu, ⁶ ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, coralruiz123@gmail.com

Introduction: With the possibility of obtaining spectra of the atmosphere of exoplanets now on the technological horizon, increased attention has been focused on determining what properties of atmospheric chemistry are indicative of the presence of a biosphere. Oxygen, ozone, and dimethyl sulfur oxide have all been proposed as possible “smoking gun” gases for the presence of life; however, all vary in their detectability, and are capable of being produced abiotically, leading to the possibility of false positives[1].

An alternative approach may be to instead examine the relationships between constituent atmospheric gases, in the form of chemical reaction networks. Previous studies[2] have examined the network structure of every significant planetary atmosphere in the solar system, and found that Earth’s is unique: the topology of Earth’s atmospheric chemical reaction network displays a hierarchical and modular structure with a scale-free degree distribution, whereas those of other planets do not. Further investigation[3] found similar results, and furthermore, that the degree distribution and scaling of Earth’s reaction network was more similar to that of metabolic reaction networks than planetary atmospheres. However, the authors also speculated that this difference may be due to the comparatively small size of the dataset for most planetary reaction networks. Nonetheless, given that similar topological signatures have already been identified in biological networks[4] and that the topology also appears to influence chemical disequilibrium in the atmosphere[5], these findings suggest the intriguing possibility that the presence of a global biosphere influences the topology of a planet’s atmospheric reaction network in a significant, detectable way.

Methodology: To verify these previous results, and further explore the use of network topology as a possible biosignature, we analyzed the network structure of several atmospheres, including those of Earth (both modern and putative early Earth), Mars, and hot and cool Jovians. A metabolic networks constructed from all biologically catalyzed reactions in the Kyoto Encyclopedia of Genes and Genomes (KEGG) was also analyzed as a proxy for the network structure

of the biosphere as a whole, to provide a point for comparison to the atmospheric networks.

Analysis was conducted by using the set of reactions at steady state to generate a graphical representation of the chemical reaction network via the Python NetworkX package. Visualization and further analysis was conducted using Cytoscape and Gephi.

Using these tools, parameters of the network topology were measured for each system investigated, including assortativity, average clustering coefficient, transitivity, average shortest path length, and the degree distribution. For determining the degree distribution we used the power law package, which applies methodology in [6] that more rigorously distinguishes cases that where the degree distribution truly follows a power-law than what was done in previous approaches.

Results: Our results are consistent with earlier findings that topological properties can distinguish different planetary atmospheres. The majority of networks studied were too small to confirm whether or not they are indeed scale-free (a power-law fit to the degree distribution could not be confirmed nor refuted). Analyzing other topological measures suggests that biology, atmospheric composition and physical variables such as T and P all contribute to the large scale structure of atmospheric reaction networks. These initial results suggest that network topology may be able to indicate the presence of a global biosphere, but that further work must be done to characterize the imprint of biology on large-scale organizational features of atmospheric chemistry.

References: [1] Wordsworth R. and Pierrehumbert R. (2014) *Astrophys. J. Lett.* 785,2. [2] Sole R.V. and Munteneau A. (2004) *EPL* 68, 2. [3] Holme P. et al. (2011) *PloS One* 6, 5. [4] Jeong H. et al. (2000) *Nature* 407, 651-654 [5] Estrada E. (2012) *J. Math. Chem.* 50, 1363-1372 [6] Clauset A. et al. (2009) *SIAM Rev.* 51.4, 661-703