CLUSTERED SIMILAR EXO-ATMOSPHERES AS AN INDICATOR OF TERRAFORMING.

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Objective: Detection of extra-terrestrial intelligence via a search for statistical evidence of terraforming in exoplanet atmospheres.

Motivation: The detection of technologically advanced extra-terrestrial lifeforms requires either receiving an intentional signal or observing indicators of alien technology. The search for direct signals assumes that an advanced civilization is making an active effort to broadcast its existence, either through directed optical or radio messages, or other methods of announcing a civilization's presence, such as a beacon or the modification of the spectral signature of a star [1,2]. When no active attempt at contact is being made, advanced civilizations can still be detected from indirect indicators of technological presence, so-called interstellar archaeology [3]. Examples of footprints of alien technology that may be observed include evidence of the astro-engineering of stars near the end of their lives, non-naturally occuring compounds in exoplanet atmosphereres, and Dyson spheres. We propose that statistical evidence of terraforming could act as an additional indicator of technological presence.

The Terraforming Footprint: The process of terraformation, or modifying a planetary body's atmosphere to make it habitiable for a species, may be a common practice employed by intelligent spacefaring civilizations to make it easier to colonize planetary bodies in a civilization's home system or in nearby stellar systems. Instead of building colonies on other worlds in controlled atmospheric environments, the terraformation process modifies the entire atmosphere of a planet to suit unconstrained habitation. However, because species generally evolve to live in certain atmospheric and environmental conditions, a terraformed atmosphere would have to contain a specifically constrained composition to ensure its habitability. For example, the human body has evolved to thrive in the Earth's atmospheric environment (1 bar with 21% oxygen), and could only survive in an atmosphere that satisfies certain compositional requirements. An atmosphere suitable for human life requires an air mixure of 500-5000 mbar, O_2 levels of 130 to 300 mbar, N_2 levels >300 mbar, and CO_2 levels <10 mbar [4]. Similarly, if an alien species originated on a planetary body with a particular atmospheric composition, the species would likely be constrained to live in atmospheres with a degree of similarity.

If a spacefaring civilization is terraforming planetary bodies in the same system or nearby systems, it would create a spatially clustered group of planetary bodies with unusually similar atmospheres. The naturaly occurance of spatially clustered terrestrial planetary bodies with similar atmospheres is expected to be very rare; the atmosphere is the most volatile component of a planet, and the atmospheres of Earth, Venus, Mars, and Titan are all comparatively distinct and have varied drastically over the history of the Solar System. While gas giants may have similar atmospheric compositions, the atmospheres of terrestrial planets and satellites are much more varied. A terrestrial atmosphere is a small fraction of its planetary body's mass, and is greatly affected by incident solar radiation, volatile delivery/escape, and geophysical processes. For example, the Earth's atmosphere has been heavily modified over the course of its evolution, widely varying throughout various epochs and highly influenced by the evolution of life and photosynthesis [5,6].

Therefore, from an observational perspective, evidence of terraforming could be reflected by the presence of two or more planetary bodies in a planetary system or group of nearby systems that have similar atmospheres of statistical significance. For example, a terraforming human civilization would produce a cluster of planets in our Solar Sytem and/or neighboring systems with similar atmospheres (O_2 levels 120-300 mbar, air mixtures 500-5000 mbar, etc.), which is very unlikely to occur naturally. While a terraforming alien species would likely not have the same compositional constraint (we have no idea what type of atmosphere an extra-terrestrial species might consider breathable), the process of terraforming should produce an unnatural cluster of planetary atmospheres with similar compositions.

Search Feasibility: Because the detection of a cluster of terraformed planets only requires observing similarities in the bulk composition of extrasolar planetary atmospheres, it should be technologically feasible in the coming decades. Space telescopes such as James Webb and WFIRST will provide initial measurements of some terrestrial exoplanet atmospheres, and subsequent telescopes will gradually increase our ability to conduct large surveys of terrestrial exoplanet bulk atmospheric compositions.

Comparison of bulk atmospheric composition should prove more feasible in the near-term than direct detection of atmospheric components that indicate biological or industrial activity. For biomarkers, direct observations of specific compounds, such as N_2O, O_2, O_3, and CO_2, could indicate the presence of alien life [7]. However, it is difficult to prove that a certain mixures of gases can only be produced biologically, and any detection of biomarkers will likely spark prolonged scientific debate regarding the biotic/abiotic origin of the signature compound(s). And while a significant abundance of certain combinations of biomarkers, such as CH_4 together with O_2, could strongly suggest the presence of life [8], life that exists under different atmospheric conditions (methane based, for example) may be difficult to distinguish from abiotic origins. Furthermore, even if biomarkers prove the presence of life, they cannot be used to distinguish intelligent from non-intelligent lifeforms. Technological advancement could be indicated by observations of non-naturally occuring gases (much like byproducts of human technologies have modified the Earth's atmosphere), however, such compounds may have low concentrations that require a prohibitively high detection threshold [9]. For this reason, statistical inference of clustered terraforming from bulk atmospheric compositions may provide the a likely means to detect extraterrestrial intelligence in the near future.

Context in the SETI Effort: Clustering of planetary bodies with similar atmospheres is a passive indicator of intelligent life, meaning it does not require the alien civilization to be actively engaged in communicating. This is advantageous because it does not require a motive for an alien civilization to announce its presence, as civilizations may try to hide their existence [10]. For this reason, there are several active searches in progress for passive footprints of alien technology (e.g., domestic radio traffic) [11]. However, domestic radio traffic, such as what might be detected of our early radio signals, is likely too weak to be detected if it comes from stars sufficiently far away, and more advanced civilizations would have advanced beyond the use of radio technology in a relatively short time. Searches have also attempted to locate Dyson Spheres [12], which would manifest infrared signatures of civilizations with enough power to consume the energy of an entire star (Type II civilizations) [13]. It has also been proposed to search for 'Fermi bubbles' in which groups of Dyson spheres expand outward as an advanced civilizations builds Dyson spheres across a section of the Milky Way or another galaxy [3], a process not too dissimilar from the propagation of terraforming. However, Dyson spheres are very difficult to construct [3] and it is unclear how many civilizations would reach the capability to produce Dyson spheres. Because terraforming technology may be feasible relatively shortly after a civilization becomes spacefaring, it may be a more common occurance among intelligent alien civilizations, particularly if there is a 'Great Filter' before advancement to Type II civilizations [14].

Cataloging and searching for spatial clusters of exo-atmospheres with similar compositions could be added to the framework for SETI searches of *systemic disequilibria* caused by the presence of intelligent life [15]. Because of the rapid advances in our ability to observe bulk atmospheric compositions of terrestrial exoplanets and exomoons, searching for statistical evidence of terraforming could provide a means of inferring the presences of extra-terrestrial intelligent life in the near future.

Additional Information: This whitepaper addresses Question 3 from the SETI roadmap [15], *how can we detect intelligent life*. Machine learning might be used to differentiate between natural and unnatural clusters of exo-atmosphere compositions.

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