RARE EARTH OR COSMIC ZOO: TESTING THE FREQUENCY OF COMPLEX LIFE IN THE UNIVERSE.
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Introduction: Is Earth an exceptional and unusual place for life in the cosmic neighborhood or is the universe teeming with complex, macroscopic life? In other words, do we live on a *Rare Earth* [1] or in a *Cosmic Zoo* [2,3]? The latter has been argued for because of recent insights gained from analysis of the key innovations during the evolution of complex life on Earth. Most key innovations have evolved many times with different origins and mechanisms but the same end function. Here, we propose on how to test between the two hypotheses during the next decades, tests which require plausible advancements in remote sensing capabities targeted at exoplanets and site visits of planetary bodies in our own solar system and beyond.

Recent Progress: The number of confirmed exoplanets now exceeds 3400, with an additional nearly 5000 exoplanet candidates awaiting confirmation [4]. Yet, we do not know how many planets of those will turn out to be Earth-like, meaning the existence of multiple environmental habitats and the presence of a sizable biosphere and complex ecosystems, without which Earth, as we experience it, would not exist [5]. Thus, the existence of a second Earth may be rare indeed. On the other hand life, even complex life, may not be constrained to "twins" of Earth if the biochemistry of life itself is different. As of now, the question cannot be decided whether an exoplanet is a host for life or even habitable (but possible uninhabited).It has been argued that the transitions toward complex life will be readily accomplished given enough time and habitable conditions on a planetary body [2].

Future Remote Sensing Capabilities: One of the inherent limitations of all the methods used today to study exoplanets is that we can only see the star and planet as a combined dot. Technologies currently in the early planning stage, such as Starshade [6] will overcome this, and provide the possibility to see star and planet as separate dots. Further development of technology could allow large-scale mapping of spectral features on the planet. Even though the planet would still appear as a single dot, that dot would change brightness and color as it rotated and orbited its star. If conditions are favorable, this information could be used to get a crude map of the distribution of color on its surface, perhaps including ice caps and major continents.

There are several chemical features of life that could be detected using advanced methods. One is the presence of a gas in the atmosphere that is likely to be produced by life, and not given off by volcanoes or other, non-living processes. Single gases are unlikely to be definitive markers of life; even oxygen can be generated by some astronomical and geological processes [7]. A combination of gases would have to be detected together, such as oxygen and methane together, which would only co-exist if continually produced.

Another often cited biosignature is the Vegetation Red Edge effect [8]. Life on Earth reflects light of wavelength 750 – 1000 nm very well, which results in a sharp 'edge' in the spectrum at about 750 nm. On Earth the Red Edge is quite characteristic, but on other worlds it may not be. Studies of how plants might use light on a world with an atmosphere made mostly of hydrogen concluded that plants there would show no Red Edge [9]. And plants under water have a much reduced Red Edge, as seen from above. If an exoplanet with a 'Red Edge' could be observed, then the conclusion might be that life was or is there, but seeing no Red Edge does not prove the opposite [3].

The challenges to detect any life are formidable, and will remain so for the foreseeable future. Detecting whether that life is complex, as opposed to an ecosystem solely of microbes, is an even harder challenge. However, if we can map an exoplanet, it would be in principle possible to determine the presence of complex life on that planet or moon if:

1) the planet can be mapped remotely in a way that differences on its surface can be analyzed.
2) land can be distinguished from seas. This may be accomplished by detecting the 'glint' of sunlight reflected off the seas, just as the Cassini orbiter detected the glint of sunlight off the polar lakes on Titan (Figure 1).
3) a distinctive spectral feature attributed to life on the land can be mapped, and it can be ensured that strangely coloured rocks, dust clouds or other features are not detected instead, by mistake.

Condition (1) is extraordinarily hard. Condition (2) is beyond any present planned capability, but is not impossible. Condition (3) we do not know how to do yet, but there are some ideas. For example, land plants have a substantial local effect on climate. Due to evapotranspiration and the release of aromatic chemicals into the air, plants increase rainfall over large forests, especially in the tropics. This changes the pattern of rainfall on Earth, alters the global cloud distribution, and cools the land. Trees can do this because they have a very large surface area, much larger than the ground they are growing on. In theory, this effect could be detected on another world as has been shown from modeling of "Desert world" planets and "Green planets" [10].

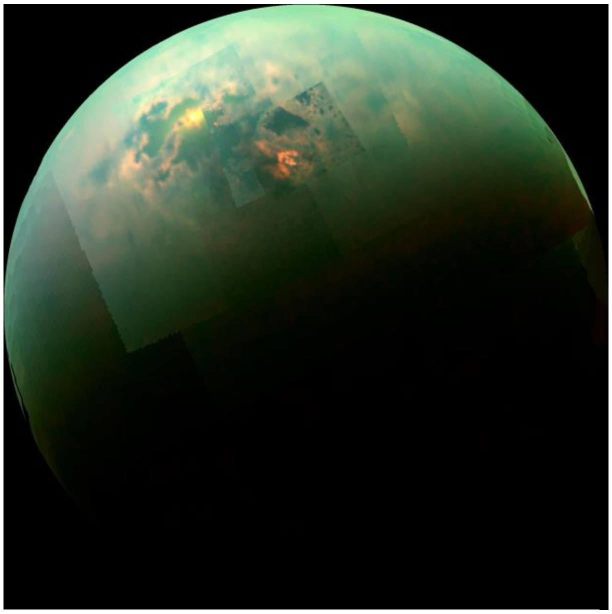

Figure 19. Near-infrared, color mosaic from NASA's Cassini spacecraft showing the Sun glinting off Titan's north polar seas. The specular reflection is the bright area near the 11 o'clock position at upper left. Image from NASA.

Site Visit: A thorough astrobiological investigation requires becoming close and personal with your object of interest. There is only so much that can be achieved with remote sensing. Ultimately, confirmation that a planet hosts complex life, and indeed confirmation that it holds life at all, must come from close examination of the planet, including sampling its surface. And even that is challenging as the Viking life detection experiments showed.

The problem, of course, is that nearly all the potential targets are so far away. Proxima b in the Alpha Centauri system is the closest exoplanet being about 4.3 light years away from Earth. A few years ago such a journey to Proxima Centauri by a robotic probe would be all but out of question, but recent developments make this more of a possibility. Spacecraft technology has become so much more compact with microsatellites like Cubesats that are also low-budget. Also, gains have been made in innovative propulsion systems such as Starwisp [11], which in principle could reach 10% of the speed of light, getting to Proxima Centauri in 43 years [12]. The Breakthrough Starshot project has updated this concept and aims to reach 20 % of light velocity (https://breakthroughinitiatives.org). And the 100 year Starship Initiative funded and supported by NASA and the Department of Defense (USA) (http://100yss.org/), has the objective to make interstellar travel a reality within the next 100 years.

Fortunately, in addition to the above we can also investigate our own solar system to test the hypotheses. Our solar system contains many marginally habitable planets and moons. None of them is suited to terran life as the Earth is, but then life on Earth is adapted to its home planet, not to another world, so it is inevitable that other worlds will be less hospitable to our type of life. But if we could find life on another body in our own solar system, we can go there and analyze it. If such life existed, it would be a very strong argument that life on Earth was not an incredibly lucky event, but that life is common, even if those environments were too harsh, limited or transitory to allow complex life to develop. So before considering a mission to Proxima b, we should consider missions to some of the main contenders of being hosts for life in our own solar system: Mars, Titan, and Europa. The case of Europa provides an especially intriguing example, because it might be the only place in our solar system where we might have a chance to find some type of complex life (but certainly not as complex as life on Earth, [13]), especially if hydrothermal vents provide a correct analogy for the origin and colonization of life on other worlds [14].

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