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Sustainability and the astrobiological perspective: Framing human futures in a planetary context

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ABSTRACT

We explore how questions related to developing a sustainable human civilization can be cast in terms of astrobiology. In particular we show how ongoing astrobiological studies of the coupled relationship between life, planets and their co-evolution can inform new perspectives and direct new studies in sustainability science. Using the Drake Equation as a vehicle to explore the gamut of astrobiology, we focus on its most import factor for sustainability: the mean lifetime $\bar{L}$ of an ensemble of Species with Energy-Intensive Technology (SWEIT). We cast the problem into the language of dynamical system theory and introduce the concept of a trajectory bundle for SWEIT evolution. We then discuss how astrobiological results usefully inform the creation of dynamical equations, their constraints and initial conditions. Three specific examples of how astrobiological considerations can be folded into discussions of sustainability are discussed: (1) concepts of planetary habitability, (2) mass extinctions and their possible relation to the current, so-called Anthropocene epoch, and (3) today's changes in atmospheric chemistry (and the climate change it entails) in the context of pervious epochs of biosphere-driven atmospheric and climate alteration (i.e. the Great Oxidation Event).

Introduction

Anthropogenic global climate change is currently recognized as a significant, perhaps fundamental, issue facing human civilization (Solomon et al., 2007). The chemical composition of the Earth's atmosphere has been significantly altered by human activity. Moreover, detailed analysis of global data sets has implied the potential for driving the climate system into a state quite different from the one in which human civilization has emerged and flourished (Parry et al., 2007). Recognition of the likelihood of profound climate change has thus led to the desire to sustain, to some degree, the current climate state. Climate science is, however, just one domain in which discussions of "sustainability" have emerged. It has also gradually become apparent that human activity has been driving many other changes in the coupled "earth systems" of atmosphere, hydrosphere, cryosphere, geosphere and biosphere in ways that could threaten, or at least strongly stress, the so-called "project of civilization."

Such changes to the earth systems include: (a) the depletion of natural fisheries where it is estimated that 95% of all fish stocks have suffered some form of collapse over the last half century (Worm et al., 2006); (b) diminishing supplies of fresh water (Gleick, 2003); (c) loss of rain forest habitat (Williams, 2003); and (d) continuing acidification of the oceans (Cicerone et al., 2004). In all cases human activity, integrated over time and location, have led to substantial changes in the state of the coupled earth systems. These changes have been dramatic enough for some researchers to begin speaking of the beginning of the Anthropocene, a new, geological epoch succeeding the Holocene (the current interglacial period; Zalasiewicz et al., 2010).

The field of sustainability science has emerged in the wake of this recognition seeking to understand the interactions "between natural and social systems" (Kates, 2011a,b). In particular this discipline studies how such interactions can lead to new modalities of human development that meet "the needs of the present and future generations." Sustainability science, bridging disparate domains such as sociology and Earth Systems Science, has grown rapidly. More than 20,000 articles have appeared addressing sustainability science over the last 40 years with a doubling in the number of articles every 8 years (Kates, 2011a). Although sustainability science often focuses on place-specific issues, by its very nature it requires a global perspective to address

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issues associated with the need to "conserve the planet's life support systems" for future generations (Kates, 2010). This trend is clear in recent studies exploring planetary-scale tipping points (Lenton and Williams, 2013) or the existence of planetary-scale "boundaries" as safe operating limits for civilization (Rockstrom, 2009). In this way sustainability science and the theoretical perspective it takes on the trajectory of human culture is necessarily global, or better yet *planetary*. It is from that perspective that sustainability science overlaps with the domain of another young and rapidly growing field: astrobiology.

Astrobiology is essentially the study of life in an astronomical context (Sullivan and Baross, 2007). The NASA Astrobiology Institute, for example, defines its subject as "the study of the origin, evolution, distribution, and future of life in the universe". More specifically, since most extrapolations involve a planetary context for the origin and evolution of life, astrobiology is concerned with planetary issues just like sustainability science.

Astrobiology faces an obvious "$N = 1$ dilemma" in that we have only one known example of life in the universe (more on this in Section 'The Drake Equation and its longevity factor *L*'). Nevertheless, since the 1990s there has been an explosion in new studies and new results relevant to astrobiology's core questions. For the purposes of this paper we break these advances into three research domains (though there are others that are of broader import):

1. *Exoplanets*: the discovery of planets orbiting other stars and the characterization of exoplanetary systems in terms of habitability for life (Lineweaver and Chopra, 2012).
2. *Solar system studies*: the detailed (often *in situ*) exploration of planets, moons and other bodies in our own planetary system with a focus on the evolution and history of habitable locations (i.e., liquid water, sources of free energy for metabolism, etc.) (Lineweaver and Chopra, 2012; Arndt and Nisbet, 2012).
3. *Earth system studies*: the detailed investigation of the Earth's history including the history of the 3.5-Gyr-old biosphere and its coupled interactions with atmosphere, oceans, ice regions and land masses (Azua-Bustos et al., 2012; Coustenis and Blanc, 2012).

The most notable discovery in astrobiology relevant to exoplanets (domain 1) has been the recognition that planets are quite common in the Galaxy, with more than a billion Earth-mass-like worlds expected to exist on orbits within the habitable zones of their stars (Seager, 2012). Relevant to solar system studies (domain 2) we now recognize that Mars once hosted liquid water on its surface and that many of the moons of the gas and ice giant planets harbor subsurface liquid oceans (Castilo-Rogez and Lunine, 2012). Relevant to earth systems science (domain 3), we realize that the biosphere and non-biological Earth systems have, at least during some epochs, *co-evolved*, meaning that significant feedbacks have led to substantial changes in the evolution of the entire earth system. The development of an oxygen-rich atmosphere due, in part, to the respiration of anaerobic bacteria is one example of such co-evolution (Kasting and Canfield, 2012). The evolution of various mineral types has also been strongly influenced by the presence of life (Hazen et al., 2008).

Thus astrobiology takes an inherently large-scale and long-term view of the evolution of life and planets. In this way the data, the perspective and conceptual tools of astrobiology may cast the global problems of sustainability science into a different and, perhaps, useful light. In particular, the astrobiological perspective allows the opportunities and crises occurring along the trajectory of human culture to be seen more broadly as, perhaps, critical junctures facing *any species* whose activity reaches significant level of feedback on its host planet (whether Earth or another planet). In this way, the very question of sustainability may be seen not solely through the lens of politics and policy decisions (Kates, 2010), but also as an essential evolutionary transformation that all (or at least many) technological species must experience.

In this paper we explore the argument that perspectives developed through astrobiological studies can usefully inform sustainability science by broadening its understanding, providing case studies, and suggesting different modes of conceptualization. In particular, we seek to frame a research program that might allow researchers to develop a better understanding of the types of trajectories a biosphere might follow once a generic Species with Energy-Intensive Technology (*SWEIT*) emerges.

We begin in Section 'The Drake Equation and its longevity factor *L*' with a discussion of the relevance of astrobiology, using the standard Drake Equation as a vehicle for framing our questions. In addition we use the Drake equation to address the concept of a statistically relevant ensemble SWEITs. We then discuss in Section 'Trajectories of technological energy-intensive species' possible theoretical tools for modeling sustainability from an astrobiological perspective with an emphasis on dynamical system theory. In Section 'Areas of astrobiology relevant for sustainability science' we present three examples of specific astrobiological topics that can inform sustainability: definitions of habitability across time, the occurrence of mass extinctions, and the biosphere driven climate change as a consequence of SWEIT activity. Finally, in Section 'Discussion and summary' we summarize our findings as well and discuss possible directions for future research.

The Drake Equation and its longevity factor *L*

Historically the Drake Equation has been instrumental in framing discussions of astrobiology. Originally proposed by Frank Drake in 1962 as a means for estimating the present number (N) of radio-transmitting cultures, the equation cleanly parses the question of life and its evolution into astronomical, biological and sociological factors (Tarter, 2007). Note that the original intention of the Drake equation was to estimate the number of civilizations detectable today. Since we are interested in the question of SWEIT lifetimes, detectability is not our concern. Instead our first goal is to use equation to estimate the number of SWEITs that exist now or have already gone extinct.

In its traditional form the Drake Equation is

$$N = R_* f_p n_e f_l f_i f_t L, \tag{1}$$

where R_* represents the rate of star formation in the Galaxy, f_p is the fraction of stars that host planets, n_e is the mean number of planets in the so-called habitable zone[1] of those stars with planets, f_l is the fraction of those planets where life forms, f_i is the fraction of life-bearing worlds that evolve intelligence, f_t is the fraction of intelligent species that develop radio transmissions, and L is the mean lifetime of such a transmitting technological species. In this paper we broaden the usual definitions of f_t and L beyond solely radio transmission to consideration of the emergence and longevity of *any* SWEIT, whether or not radio technology is involved.

Many analyses have been made attempting to produce estimates of N relevant to radio-based searches for other technological civilizations (Wallenhorst, 1981; Pena-Cabrera and Durand-Manterola, 2004). Although early work on this problem constituted a kind of educated guess work, those efforts were nevertheless useful in helping to structure debate about factors

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[1] In this paper we use the traditional definition of *habitable zone*: the range of orbital distances from its host star in which a planet's surface could have stable liquid water (taken as the *sine qua non* for life). We note that there may also be "galactic habitable zones", i.e. regions of the galaxy that are hospitable to the formation of habitable worlds (Lineweaver et al., 2004; Suthar and McKay, 2012).