Star Maker: Reshaping the Archipelago of Habitability

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The question of the ultimate limits of physics can be construed in two different, but closely related, senses: as (1) *What is ultimately knowable in physics?* and as (2) *What is ultimately doable in our physical environment?* I argue that, while we may soon have understood the origin of what is conventionally meant by "physics"—a particular low-energy limit ("vacuum") of the string theory or any alternative unified field theory—such knowledge needs to be supplemented by a complete understanding of the observation-selection effects. In particular, precise determination of the habitable region in the parameter space will enable us to explain the very origin of physics in naturalistic terms and, thus, circumscribe all possible physics knowledge. Precise cartography of this huge Archipelago will enable the act of ultimate engineering: transcending effective dynamical laws and modifying entire spacetimes for the benefit of self-aware substructures (i.e., observers).

1. Multiverse and Archipelago

> The idea of one Universe... is preposterous.
>
> John Archibald Wheeler

Evidently, we live on a small island. Seemingly paradoxically, it is small although one of a few physical facts we may be certain about it is that it is massively larger than the visible universe of astronomers. We have not yet ventured much beyond our immediate locale on this small island; even our own inconspicuous location still holds great mysteries for us. It seems that we find ourselves near the mountain peak on our island, but even that is uncertain. Only recently we have discovered that there are other islands besides our home scattered in a vast (possibly infinite) ocean. And the ocean is dead—empty of any *conceivable* form of life; it epitomizes the absence of life itself. But we have made our first attempts at mapping our surroundings and, in particular, sketching the outline of the ocean shores. In this, some of us bear similarities to the great adventurers of the Age of Exploration in the XV and XVI centuries; only in this case the explorers are not sea-captains and conquistadors, but theoretical physicists, cosmologists and philosophers.

Before I explain the central metaphor of the *Archipelago of Habitability*, I wish to emphasize how difficult and different from our modern experiences cartography once was [1]. Visualize in the mind the huge tasks facing the explorers of old–for instance, that of mapping a newly discovered South Seas archipelago employing the rather basic geographical and navigational means then at their everyday disposal. No *Google Earth* or aerial or orbital reconnaissance survey images or ground-truth photography. On the contrary, the explorers of old had to rely on quite uncertain and imprecise navigational aids. It is hardly a wonder that their maps were usually very imprecise in their general details, at best inaccurate and often fanciful. This is a point to imagine when we discuss this much vaster and more abstract Archipelago.

Dramatic developments in the last 10-20 years mark a new intellectual convergence, especially the emergence of the "new standard" cosmological model of the flat universe dominated by dark energy (after 1998), connected with the predominance of the inflationary paradigm, and the "astrobiological revolution" (after 1995), offering a new unified framework for the old set of obvious questions about the place of life and intelligence in the cosmic context [2,3]. In fundamental physics, the rise of string theory as the best candidate for the 'Theory of Everything' and the realization that it has a huge number of low-energy sectors (vacua) forming a 'landscape' [4,7], naturally connected to the elucidation of anthropic principle(s) as observation selection effects [5], leading to rejection of the old-fashioned teleological misinterpretations. All these developments have contributed to the tremendous increase in work on various theories of the *multiverse*. In general, a multiverse is a set of large, causally connected cosmological domains—conventional universes. The multiplication (*sic!*) of multiverses has occurred over a wide spectrum of disciplines, from cosmology to quantum information theory to philosophy: see Tegmark's review [8] and the popular books of Rees, Vilenkin or Susskind [6,7] on the subject. In this essay, I shall use the anthropic landscape of string theory as the prototype physical realisation of the multiverse, while strongly emphasising that it serves just as a placeholder and that no conclusion is crucially dependent on the choice of ultraviolet completion of the effective field theory.

The idea of the Archipelago of habitability was introduced by Max Tegmark in his intriguing paper on the relationship between mathematical and physical worlds [9]. Conceptually:

> **The Archipelago of habitability**: a set of regions in the parameter space describing those parts of the multiverse which are hospitable to life and intelligent observers of any kind.

Physically, the Archipelago is a subset of the anthropic landscape of either string theory or any other overarching 'Theory of Everything' with multiple low-energy solutions ('vacua'). Thus, the Archipelago is part of the abstract space defined by whatever physics determines the structure of the multiverse. It is both logically and physically contingent on the reality of the multiverse; but that is still not saying much, since simple variants of the multiverse are rather uncontroversial and legitimate consequences of our firmly established cosmological theories [8,10]. Whether the multiverse is infinite, as in the currently popular eternal inflation, or finite, as in some construals of the string theory landscape, reflects directly on the structure of the Archipelago as well.

What is an island? It is a set of parameters describing habitable universes which are close in parameter space; whether we can specify the meaning of 'closeness' beyond simple intuition depends crucially on the structure of the multiverse itself. In other words, the multiverse imposes a natural—or at least a convenient—metric upon the Archipelago. By definition, there is at least one island in the Archipelago—our home island. If the multiverse contains arbitrarily small variations in the constants of nature or cosmological parameters or even the mathematical shape of physical laws, then it is reasonable to conclude that the Archipelago is as dense as the remainder of the multiverse; e.g., it is clear that the change in the coupling constants of 1 part in 10^{50} (not those actually measured, since we are unable to measure them to such precision yet!) will not change anything in the habitability status of our universe. If such minuscule variations are realized within the multiverse, a universe otherwise described by identical laws and parameters to ours also belongs to our habitable region = our home island. Various constants and parameters of the multiverse play the role of geographical coordinates in maps of terrestrial archipelagos. If we start on a land point in, say, Sumatra, and continuously change either longitude or latitude along any chosen direction, we are bound to end up in the ocean. Similarly, if we start with a universe like ours and continuously change some parameter—the strengths of forces or the cosmological constant—we shall inevitably end up in a universe lacking pre-requisites for life and observers. However, in the same manner as it is possible to start in Sumatra and by a non-continuous increase in longitude to end up in some other island, for example Borneo or Bali, it is possible that after a large interval of non-habitability, our parameter again enters an interval which (with appropriate changes in other parameters) enables the existence of observers.

A prediction of the existence of a small positive cosmological constant in the anthropic manner more than a decade before its observational discovery is often attributed to Steven Weinberg [11]. This was an important theoretical success which opened the way for dramatic expansion of anthropic arguments in cosmology. In the current cottage-industry of multiverse predictions, a special role is reserved for the equation giving a probability that some observer anywhere in the multiverse measures a feature *X* [12]:

$$p(X) = \frac{\sum_n \sigma_n(X) V_n \rho_n^{\mathrm{obs}}}{\sum_n V_n \rho_n^{\mathrm{obs}}}, \tag{1}$$

where the index *n* labels all possible vacuum states (all different low-energy '*physicses*' or different universes); in current versions of string theory there is a finite number of such states, although it is huge (10^{500} or so; cf. Ref. 4), but in principle it could be infinite. The latter case could pose some interesting problems in the theory of probability, but in general will not preclude the usage of Eq. (1) with appropriate weightings. V_n is the spacetime volume belonging to the universe *n*, ρ_n^{obs} is the density of observers in the same universe, and

$$\sigma_n = \begin{cases} 1, & \text{if universe } n \text{ has property } X \\ 0, & \text{otherwise} \end{cases}. \tag{2}$$

In principle, V_n is calculable from our understanding of cosmological physics, although in weird enough universes it might be impossible to calculate in practice (or at least in finite time available to human cosmologists!). It is also likely to be infinite in some or most of the universes, so an appropriate weighting procedure is necessary. Of course, the biggest uncertainty comes from the quantity ρ_n^{obs}, the density of intelligent observers. It is usually assumed to be proportional to the density of galaxies,

$$\rho_n^{\mathrm{obs}} \propto \langle \rho_{\mathrm{gal}} \rangle_n, \tag{3}$$

the latter being the main features of the structure of our own universe.

How can the concept of the Archipelago of Habitability help us elucidate Eq. (1)? Obviously, even islands of identical shape on the map can have vastly different habitabilities – the universes in two groups could have a vastly different density of observers. We have, thus far, discussed only surface coordinates of islands in the Archipelago; but their essential property (making them islands in the first instance) is their altitude profile. Very high points (analogs of the volcanic peaks that are the Hawaii islands) represent sets of parameters describing extremely bio-friendly universes, in contrast with bare rocks protruding from the waters, where life-forms are possible, but unlikely or rare. The same pertains to intelligent observers: regions of high altitude will contain the predominant fraction of the entire set of observers in the multiverse. These regions correspond to high values of ρ_n^{obs} in such parts of the parameter space. Contrariwise, the limit

$$\rho_n^{\text{obs}} \xrightarrow[a_i \to a_i^0]{} 0 , \qquad (4)$$

(for each theory parameter a_i) delineates the “sea level” line and thus the boundary of the Archipelago.

Thus, in order to make anthropic arguments cogent against the background of the Archipelago, we need to weight universes by their ‘altitude’, i.e. the measure of habitability. As discussed above, the very definition of the Archipelago is contingent upon resolving the issue of criteria for life to arise in a naturalistic manner. But in order to get the altitude profile, we need much more further effort—we need, at least, some hold on the emergence and dynamics of intelligent observers, traditionally the province of SETI studies (and the recreational discourse of SF novels and movies). No discontinuity here: by studying already ‘traditional’ astrobiological themes, like the Galactic Habitable Zone (GHZ) [13], we expect to survey viable SETI targets and assess the density of extraterrestrial civilizations, even if specific modifications are made when we consider intelligent observers rather than just complex life. In practice, this task is huge; perhaps generations of astrobiologists will pass before we get close to quantitative precision. But the enormity of the task should not detract from the fact that it is **a well-defined problem** from the start.

2. Astrobiological Map-making

Wonder if he'll ever know
He's in the best selling show
Is there life on Mars?

David Bowie

We are lucky enough to live in an epoch of great progress in the still nascent discipline of astrobiology, which investigates three canonical questions: How does life begin and develop? Does life exist elsewhere in the universe? What is the future of life on Earth and in space? A host of important discoveries has been made during the last decade or so, the most important being the discovery of a large number of extrasolar planets whose number increases almost weekly; the existence of many extremophiles; the discovery of sub-surface water on Mars and the huge ocean on Europa; the unequivocal discovery of amino-acids and other complex organic compounds inside recovered meteorites; the quantitative treatment of GHZ; the development of a new generation of panspermia theories, spurred by experimental verification that microorganisms can easily survive conditions of an asteroidal or a cometary impact, etc.

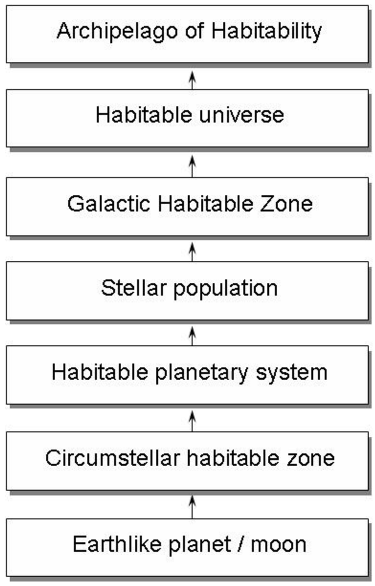

Figure 1. Archipelago of Habitability is the logical completion and generalization of our concept of habitat.

One new role for astrobiology is the mapping of the Archipelago of Habitability which is, it is worth repeating, a continuous part of the general parameter landscape—with the sea level defined on the basis of our understanding of habitability. Even more, habitability determines the altitude profile of an island: how high will it be, will it have steep or shallow slopes, the vast expanse of the plains, and so on. We all agree that our universe is hospitable to at least some forms of life and there is very strong empirical evidence that significant changes in values of some or all parameters will lead to an inhospitable universe (the subject matter of classical anthropic 'fine-tuning' [15,16]). Asking about the seashores of the Archipelago is tantamount to asking Schrödinger's famous question *What is life?* [17].

There are many ways of surveying the Archipelago, just as in terrestrial geography one can either do satellite imaging, or search for water, or do mineral prospecting, and so on. Research dealing with preconditions for life and observership as we know them in a physical, chemical or geological sense is a part of the mapping endeavour. A particular form of surveying is embodied in research on *artificial life* (A-Life). From a rather eccentric game of computer scientists (albeit one with august ancestry, with von Neumann), it has become an important mainstream research discipline with wide-ranging influence within fields such as evolutionary computation, cellular automata, genetic algorithms and even evolutionary art [18]. It is often stated that the goal of A-Life is to **recreate** biological systems in a digital environment, but there are some distinguished researchers, such as Thomas Ray, who claim that such experiments are actually **creating** a new kind of life. If this strong A-Life thesis turns out to be correct, this will have important epistemological implications for cosmology as well, since numerical experiments of Ray's type would make the seashores of the Archipelago amenable to much more precise probing—something startingly similar to the revolution caused by Mercator and Ortelius in cartography in the 1560s.

Most pertinently to our goal, we can ask, with Tegmark [9] what are the minimal conditions for a physical environment containing intelligent observers. Tegmark lists three basic conditions, namely **(1) complexity, (2) predictability**, **(3) stability**. The first condition is almost self-evident: even the most ardent physicalists are unlikely to deny that an excessively high level of complexity is the main reason why science has not yet managed to create living or intelligent beings in any laboratory. The other two criteria are meaningful if we consider the operation of measurement by which knowledge is received by observers, which requires both that the results do not fluctuate so greatly in the past or the future, so as to preclude the use of inference from past experience and the existence of habitable conditions during measurement. The search for the sufficient criteria, and thus the outlines of the Archipelago, continues.

3. Voyages of Discovery

> Mathematics is applied to the real world and has proved fruitful... We should judge reality by the little which we truly know of it.
>
> Kurt Gödel

Cartography would be senseless without an appropriate metric; in the terrestrial case, the units of length combined with the angular coordinates, provide us with a hugely successful description of any explored piece of landmass or ocean. The extension of our analogy to the cartography of the Archipelago emphasizes the analogous role of changing various parameters of physics (including the very form of low-energy physical laws). Classical anthropic arguments from fine-tuning amassed empirical evidence that we cannot change the parameters that describe our universe **very much**, at least as long as we keep other parameters constant. This would mean that our island is a rather small one, since even small changes in any single coordinate (other coordinates fixed) would lead us quickly to the ocean shore. Therefore, it seems natural that early anthropic thinkers concluded that our island is the only one in existence. They were wrong, but not because of some ulterior agenda—we might compare their rationality to that of a hypothetical ancient philosopher of Rapa Nui, pondering the huge ocean surrounding his apparently isolated homeland.

But the contemporary sailors of the Archipelago have refuted this prejudice. In the often cited and almost as often poorly understood study, Aguirre finds a 'cold' Big Bang model—a counterfactual one with low entropy-per-baryon in comparison to our actual Big Bang—which is habitable even according to high standards posed by the **terrestrial** kind of life [19]. This type of universe is capable of producing structure, such as galaxies and stars, as well as the chemical building blocks of known life-forms; and there is sufficient time for chemical and biological evolution in such an astrophysical environment. What Aguirre does, in fact, is to discover another habitable region in the parameter space—**another island of habitability**! The role of astrobiology finds expression in the significant endnote of Aguirre's paper, in which he states:

> I have assumed that the number of independent measurements in a subuniverse is proportional to the number of suitable stars, neglected such effects as, for example, high metallicity leading to more planets upon which multiple civilizations might arise in a single solar system. I have also neglected factors like extinction-causing impacts, radioactivity-induced plate tectonics, etc., which are possibly but not clearly necessary for the evolution of observers.

Thus, we need astrobiological knowledge from our universe, even when dealing with other, disconnected parts of the Archipelago.

But Aguirre's is not the only other island discovered so far. In fact, the region found by Harnik, Kribs & Perez [20] is both larger and more remote from our home universe: they investigated nothing less than a set of conceivable universes without weak interaction ('weakless' universes):

> We do not engage in discussion of the likelihood of doing simultaneous tunings of parameters nor the outcome of statistical ensembles of parameters... Instead, we are interested in 'running the universe forward' from a time after inflation and baryogenesis through billions of years of evolution. We will exploit the knowledge of our Universe as far as possible, adjusting standard model and cosmological

> parameters so that the relevant micro- and macro-physical outcomes match as closely as possible. We emphasize that this is really a practical matter, not one of principle, since any significant relaxation of the 'follow our Universe' program would be faced with horrendously complicated calculations... There is probably a wide range of habitable universes with parameters and structures that look nothing like our Universe. For us, it is enough to find one habitable weakless universe about which we can make the most concrete statements.

This truly looks like a bold sailors' manifesto! The difficulties that are bound to be encountered by any straying explorer into these dangerous waters ('horrendously complicated calculations') are explained, and the independence of the basic approach to the form of the multiverse (string landscape or any other) explicated. This makes the results of the study still more impressive, since they find an apparently habitable universe missing so crucial an ingredient of our world as one of the four fundamental low-energy interactions.

Why, then, do these authors repeatedly perceive themselves as refuting anthropic arguments? First, most anthropic arguments in the literature (e.g., setting of the electroweak scale, criticized by Harnik et al.) are narrowly or badly formulated. They are based on calculations of the effects of small changes in a small number of parameters, and not on a true **insight** into the underlying physics, which could indicate the way in which multiple parameters could be varied—at least in principle—whilst retaining habitability. A clear parallel here is with the misguided "rare Earth" arguments in astrobiology: if there were no Jupiter in the Solar System, the Earth would have been catastrophically bombarded by large comets and complex life would have been impossible [21]. This contains an internal contradiction: If there were no Jupiter, there wouldn't have been a Solar System as we know it at all! It is doubtful whether the Earth would ever exist in such a scenario, and everything else would have been different as well, so the comparison to the realistic case is pointless.

In addition, the widespread perception of anthropic principle(s) as teleological naturally leads to the erroneous conclusion that habitability is, if not identical with the criteria for evolution of *homo sapiens* (such an extremist position is relegated to ID proponents), than at least **centred** on it. This logic is anthropocentric and flawed; it has nothing to do with the real meaning of anthropic reasoning. It may well be true that we are indeed living on an island (after all, even Eurasia can be regarded as a huge island!), but the justification for it is wrong.

In a more general sense, studies such as that of Chavanis on white dwarfs in an arbitrary number of dimensions, or Adams on stellar evolution with unconventional parameters [22], are part of the research helping us elucidate the Archipelago. We do not perceive direct connections between us and white dwarfs at present, but the elegance and simplicity of the problem in *D* dimensions gives us a feel for the approaches and ways of thinking necessary to sketch out the cartographical task. Obviously, interest in this sort of research has increased significantly—we might be on the verge of a true Age of Multiverse Exploration! In such a precise cartography, in determination of all the seashores, beaches, gulfs, estuaries, coves, firths, reefs, and lagoons lies the ultimate knowledge of physics.

4. Ultimate Limits: Reclaiming the Land?

> ...and gather me
> Into the artifice of eternity.
>
> William Butler Yeats

So far, I have argued that a useful bridge between cosmology and particle physics on one side, and astrobiology on the other, can be achieved immediately through an exploration of cosmological parameter space. The Archipelago of Habitability—the set of habitable domains in the multiverse—appears to be a useful metaphor which directs our efforts towards a comprehensive elucidation of the true relationship between cosmology and astrobiology in a wider perspective [23].

Beyond it is the annihilation of the perennial dichotomy between “natural” and “artificial” [14]. There is no reason why speculation following the Rennaissance ideal of *vita activa* should be less bold than those inspired by *vita contemplativa*. In recorded human history, navigation has been followed by colonization; especially relevant are the cases of colonization of previously uninhabited islands, like Cape Verde or the Falklands. Increase of human knowledge (in the final analysis, **physics** knowledge) has been inexorably followed by adjusting even hostile conditions for human economic use and habitation. The same general pathway applies to currently discussed ever more detailed plans for permanent manned bases on the Moon, orbital habitat stations and—in the long run—terraforming other planets and satellites. In essence, all this reduces to extension of the habitable part of parameter space within our actual vaccuum physics.

Where could this end in the future times for intentional action accorded to us—and other intelligent observers in the multiverse—by physical eschatology [24]? Could the rules be changed, at least in principle and, in the fullness of time, parts of the landscape modified by intentional influence, like the building of artificial islands in today's world? Fortunately, at least two visionary pioneers strode with giant steps in that direction: Olaf Stapledon and Stanislaw Lem. In the last quarter section of Stapledon's *Star Maker* (1937), we are offered an “internal” perspective on the creation of universes [25]. As the narrator accesses larger and larger spatial and temporal scale in Stapledon’s strange novel, the distinction between untamed nature and the “artifice of eternity” dissolves. “The cosmos which he now created was that which contains the readers and the writer of this book.” The creation described therein is naturalistic, but it is the human language which, indeed, fails in this limit of physical capacities: “To speak thus of the universal creative spirit is almost childishly anthropomorphic.” Some of the textual description is surprisingly fresh, considering its early-twentieth century vintage: “This most subtle medium the Star Maker now rough-hewed into the general form of a cosmos. Thus he fashioned a still indeterminate space-time, as yet quite ungeometrized; an amorphous physicality with no clear quality or direction, no intricacy of physical laws...”. It incorporates the emergence of diverse conceivable observers (as we expect in the Archipelago):

> I can, indeed, say of all these creations that, like our own cosmos, they were immensely capacious, immensely subtle; and that, in some alien manner or other, every one of them had both a physical and a mental aspect; though in many the physical, however crucial to the spirit's growth, was more transparent, more patently phantasmal than in our own cosmos. In some cases this was true equally of the mental, for the beings were often far less deceived by the opacity of their individual mental processes, and more sensitive to then-underlying unity.

Stapledon perhaps did not entirely succeed in conveying such a grand vision, but it is a glorious failure, and one still awaiting its proper inheritor; perhaps s/he will belong to the realm of physics, rather than—or in addition to—the one of poetry.

The “external” perspective is given in Lem's mind-boggling story/essay/paper *The New Cosmology*, originally written in 1971 [26]. In contrast to the timid observer of Stapledon’s novel, Lem’s narrator is a modern-day Nobel-prize winner, a somewhat cynical physicist who describes his “trivial” solution of Fermi’s paradox: *Where is Everybody?* Why don’t we perceive artifacts and engineering of supercivilizations billions of years older than ours? But, he says, we do: laws of physics themselves are product of their engineering, of the Great Game, played on largest possible spatial and temporal scales. The Players’ pool of knowledge is so vast and their capacities so overwhelming, that only “by their fruits ye shall know them”—and those are the (effective) laws of physics:

> If one considers "artificial" to be that which is shaped by an active Intelligence, then the entire Universe that surrounds us is already *artificial*... Instrumental technologies are required only by a civilization still in embryonic stage, like Earth's. A billion-year-old civilization employs none. Its tools are what *we* call the Laws of Nature. Physics itself is the "machine" of such civilizations!

He continues to explain the hierarchical levels of various "physicses" and the strategies of reconstructing, using game-theory approaches, the evolutionary pathway of our own effective laws. But his main point is clear: "[T]heoretically, if the energy Earth's science invests in elementary particle research were to be multiplied 10^{19} times, that research as a *discovering* of the state of things would turn into a *changing* that state! Instead of examining the laws of Nature, we would be imperceptibly altering them." And, again, in the anecdote, told by the narrator at the finale of his speech:

> I should like to quote... Professor Ernst Ahrens, my teacher. Many years ago, when, still a youth, I went to him with my first drafts containing the conception of the Game, to ask him his opinion, Ahrens said: "A theory? A theory, yet? Maybe it is not a theory. Mankind is going to the stars, yes? Then, even if there is nothing to it, this thing, maybe what we have here is a blueprint, maybe it will all come to pass someday, just so!"

So, Lem concludes his splendid essay, we could hope to become a Player one day and strive to increase our own island in the Archipelago.

Figure 2. The Pearl-Qatar: man-made island in the Persian Gulf.

How could such a "physics engineering" be performed? Analogy with the condensed matter physics points to reheating of a region and forcing the primordial symmetry to be broken down in a different stable vacuum configuration; thus synthetic diamonds are produced from charcoal. Either in the form of creating "basement universes" (Linde's term) in the laboratory [27], or finding and manipulating pre-existing bubbles in the Planckian substrate, the net effect is the same: creating new universes in stable vacuum states with convenient effective physics. If "convenient" is construed as habitable, this will lead to an increase in the measure of the Archipelago of Habitability. Thus, the capacities of Lem's Players (analogous to the reclaiming of habitable land from the sea by Dutch farmers or

Japanese macro-engineers) represent the answer to the question with which we started—the ultimate limit of what is possible in physics—reshaping and transforming the Archipelago into a true "artifice of eternity".

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