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lessons from the Covid-19 Pandemic

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The British Interplanetary Society promotes the exploration and use of space for the benefit of humanity, connecting people to create, educate and inspire, and advance knowledge in all aspects of astronautics.

PROTOCOLS FOR ENCOUNTER WITH EXTRATERRESTRIALS: lessons from the Covid-19 Pandemic

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This paper explores lessons evident from the Covid-19 pandemic as a framework for thinking about contact with extraterrestrial intelligence (ETI). The Covid-19 pandemic represents an opportunity to think through challenges that may arise in response to contact with ETI in part because it represents a potential threat to the entire population of Earth, thus forcing nations to implement similar measures, even if the specifics of those measures and levels of restrictions vary from one country to another. We argue that contact with ETI will not occur in a political and ideational vacuum. It will occur within an historical context and diverse cultural contexts from which people will interpret the import and risks associated with a contact event. Just as local conditions are influencing the response to Covid-19, governments and political leaders will draw on localized cultural and social conditions as they conduct risk assessments related to ETI contact and consider the value associated with managing or controlling the context and potential outcomes of a contact event. Thinking about how governments, in particular, respond to events like the Coronavirus pandemic represents an opportunity to explore how other potential existential threats to global society like contact with ETI might pan out.

Keywords: SETI, Covid-19, Pandemic, Risk, Cultural diversity

1 INTRODUCTION

Encounters with global threats to human life are not typically a part of the immediate experience of modern humans. Although there remain people who were alive during World War II and even a few who experienced the flu pandemic of 1918 as small children, the past several decades have largely been without the experience of imminent global catastrophe (although both Ebola and HIV should have been wake-up calls) – even as we have become increasingly aware that our behavior in relation to the natural environment may bring on such catastrophe in the future. Our aim in this article is to explore some of the lessons we can take from the Covid-19 pandemic as a framework for thinking about how contact with extraterrestrial intelligence (ETI) might unfold. The Covid-19 pandemic represents a useful opportunity to think through some of the challenges that may arise in response to contact with ETI in part because it represents a potential threat to the entire population of Earth, thus forcing nations to implement similar measures, even if the specifics of those measures and levels of restrictions may vary from one country to another [1].

This is particularly important given the fact that much of the literature among SETI (Search for ETI) scientists treats contact in a way that has analogies with pandemics. Although there has been some exploration of how religious differences might impact responses to ETI, it is not unusual for articles or books on SETI to begin with or reference broad proclamations of the importance of finding extraterrestrial life for humans; as one article recently put it, “the discovery of extraterrestrial intelligence...would clearly have enormous consequences for

humanity.” [2, 3] Note that the reference is to humanity – as a whole – without consideration of the cultural, political, and socioeconomic differences that exist among the people who inhabit our planet. The assumption within the SETI community, that an encounter with ETI is necessarily an event of global import and is significant for all of humanity, is open to debate. Humans are complex culturally and socially and it is difficult to see Earth as a single or unified “civilization” as is often presented in the SETI literature, rather than as a conglomeration of numerous civilizations or societies and smaller sub-groupings of larger political, economic, and social institutions and structures [4, 5]. We should be reminded of this point by the highly disparate and virtually uncoordinated country-by-country response to a clear global threat in Covid-19.

This does not, of course, mean that contact will not in some way influence all of humanity. If ETI decides to sterilize our planet – or to solve all of our social problems in surprising ways – then the actions of ETI will clearly have a global impact that involves all or most of humanity. However, this does not mean that people will interpret and react to the arrival of ETI or the awareness that ETI exists via a radio transmission in uniform or even similar ways. In other words, the significance of a global event – whether contact with ETI or the danger associated with a pandemic – is a matter of interpretation; and interpretations among humans tend to be localized rather than global [6]. This means that there is a real possibility that conflict will arise following contact, even if the intentions of ETI are benign, just as differences of interpretation of peacefully intended religious messages has frequently led to violence in human affairs – both between contact groups and within those experiencing

contact from the outside [7].

Indeed, although the focus of this article is on encounters with intelligent aliens, we should keep in mind that threats connected to contact with ETI do not necessarily involve green-skinned aliens with blasters bent on vaporizing our population. As the authors have noted elsewhere, drawing on the realpolitik approach to international affairs, contact itself has the potential to set in motion political machinations on the part of nation-states as perceived national security interests are pursued. If resources or information associated with contact, whether physical or data related to communication via technologies such as radio telescopes, are deemed important to acquire by governments, then there is the potential that contact could set in motion events which threaten global political and economic stability – even if that contact itself poses no direct threat to humanity [8, 9]. In fact, this type of scenario has already been considered as one outcome of Covid-19 for parts of the planet. As Brookings Institution scholar Tarek Yousef notes, “it is hard to exaggerate the potentially devastating impact of the ‘one-two punch’ delivered by the growing coronavirus pandemic and the spectacular collapse of oil prices” and this combination may well lead to political and economic instability as events continue to unfold in the Middle East and world as different interpretations of the situation and varied national interests further fuel an already unstable political context [10].

Contact with ETI will not occur in a political and ideational vacuum. It will occur within the context of a given point in history for the world and in various contexts related to conditions in specific parts of the world. Just as local conditions are influencing the response to Covid-19, local or global events such as recession or food shortages will no doubt have a significant influence on how humans respond to any contact scenario. And when it comes to political frameworks, governments and political leaders will conduct risk assessments related to ETI contact and consider the value that may be associated with managing or controlling the context and potential outcomes associated with a contact event. Thinking about how governments, in particular, respond to events like the Coronavirus pandemic represents an important opportunity to imagine how other potential existential threats to global society like contact with ETI might pan out.

2 SIMILARITIES BETWEEN THE CORONA PANDEMIC AND ETI CONTACT

In his discussion of the Wuhan Coronavirus response, Stewart Patrick notes that preservation of public safety depends on three key factors: “timely and credible action by governments where outbreaks occur; firm direction and leadership from the WHO in coordinating international responses; and responsible behavior of other nations that naturally want to protect their own citizens from disease” [11]. If we paraphrase this observation, it seems to apply equally to contact with extraterrestrial life, whether intelligent or not. In the event of an encounter with life from another world, public safety and health (including mental health) depend on:

- 1) timely and credible action by governments where contact is made;
- 2) clear direction and leadership from international organizations to coordinate a global response;
- 3) responsible behavior on the part of governments naturally concerned with protecting parochial national interests.

In the case of non-intelligent extraterrestrial life, such as microbial life, the parallels with the Coronavirus pandemic are obvious. Microbes are intimately and closely associated with human bodies and humans carry with them “microbial clouds” that involve a constant exchange of microorganisms [12]. We have no knowledge of exactly how introduction of an alien microorganism either into individual microbial clouds, or the ecosystem as a whole would change, and potentially represent a threat, to life on Earth. Hence, international rules for planetary protection have been in place for over 40 years, a result of the recognition that introduction of alien microbes represents a potential threat to life on Earth as well as life on any planet on which a terrestrial spacecraft might land [12]. As Ken Roy has argued, even casual contact with life that evolved in an off-earth environment could present problems for life here, because independently evolved life on another planet may use some, but not all of the amino acids used by Earth life and, thus, even slight contact with alien life could disrupt cell functions of life here. Imagine an alien life form whose skin secretes sweat that, it turns out, causes a similar reaction in humans that poison dart frogs do. A mere handshake could be lethal (or perhaps our sweat does the same to ETI) [13].

Scientists and policy makers recognize that introduction of extraterrestrial organisms on Earth has the potential to cause an Andromeda Strain type of scenario in which introduction of alien life to our planet’s environment puts human life as a whole as well as the planetary ecosystem into a context of existential threat [14]. And this issue has taken on something of a more center-stage status recently in relation to discussions within the astrobiology community raising the potential biohazard risks associated with the NASA/European Space Agency plans to return Mars samples collected by the Perseverance rover to Earth possibly in the 2030s [15, 16]. Certainly, while the introduction of extraterrestrial microbes to earth ecosystems represents a potential risk that could parallel the Coronavirus pandemic, the parallels are not limited to either direct contact with extraterrestrial life nor contact with life at a microbial level. Contact with intelligent forms of life has the potential to place our species in a position of significant risk; and a key similarity is that contact with ETI, like our current encounter with Covid-19, is a (potential) global threat necessitating a global response.

3 INTERSPECIES CONFLICT

In the remainder of this article, we will treat the Covid-19 pandemic as an interspecies conflict that implicates our planet as a whole (or at least our species) without differentiation among factors such as race, ethnicity, gender, culture, socioeconomic status, and so on (although it should be noted that early indicators suggest that socioeconomic status clearly is a factor in how Covid-19 is experienced) [17]. However, observation of the current situation via various media outlets shows that differential values among different societies and within particular societies play a significant role in how governments are responding to the pandemic. In other words, despite the fact that Covid-19 represents a global threat to human life, there is no coordinated global response. Each nation-state is largely going it alone in assessing the level of threat and developing appropriate responses to the pandemic based on their risk assessments. And rather than working cooperatively, it can be argued that many governments have even largely attempted to withdraw from the international scene as evidenced by the common first step of closing borders. For example, drawing on its experiences with containing the spread of Ebola, Uganda closed its borders and airports to everything other than cargo and emergency trans-

ports and US President Trump tweeted on 21 April 2020 that he intends to close US borders to all immigration at least temporarily [18].

Within particular countries, there are also differences and debates about how the pandemic should be handled. For example, in the US, some conservative leaders have argued for the urgency of restarting the economy, even if that means increased deaths as a result of the pandemic [19, 20]. The basic thrust of this position is that the potential suffering caused by shutting down the economy is significantly greater than the suffering caused by spread of the virus. In other words, the cure is worse than the disease. If this position becomes dominant in the US, it will have specific consequences for the progress and experience of the disease likely to be different from the consequences of long-term social distancing measures that keep the economy open in limited ways. Arguments in favor of quickly re-opening the economy are typically political or ideological in nature, which means that they reflect local cultural values. The Lieutenant Governor of one state, for example, was criticized when he apparently suggested that older Americans should be willing to sacrifice themselves for the good of the economy [20]. And various groups have interpreted the risk itself in quite different ways. While the majority have viewed social distancing as a necessary practice to slow spread of the disease, some groups such as conservative evangelicals have pushed back against the policy. One televangelist, for instance, denigrated pastors who cancelled services and encouraged the use of hand sanitizer as losers and “pansies” who should quit the ministry and burn down their churches [21].

Conservative politicians who have shown interest in re-opening their state economies have been limited in their abilities to do so without significant pushback. For example, Governor Greg Abbott of Texas ended up developing a measured approach to restarting the state economy that responded to the desires of the business community to start work and the advice of health professionals and economists warning that there were significant risks associated with a premature re-opening of business as usual [22]. The result was a plan that balanced these interests and, rather than having a full restart, proposed a series of incremental steps that would slowly reopen the economy of the state.

At the same time, other countries, such as Sweden, have elected to refrain from a national-emergency policy that shuts down social activity and business, instead following a more relaxed approach, refraining from government mandates for social distancing and shutting down some types of social contexts (such as sporting events) while keeping others open. For example, elementary and middle schools have remained open, while high schools have been closed; the argument being that people with younger children cannot continue to work if elementary and middle schools are closed. The Swedish approach has focused on protecting groups at highest risk, such as the elderly, rather than shutting down society as a whole, which is different from most of the rest of Europe and parts of other countries such as the United States. Thus, even a quasi-supra-governmental body like the EU is running into barriers to coordinated action.

Places like Singapore, Hong Kong, and South Korea have responded with aggressive testing practices that have helped with suppressing the spread of the virus. Hong Kong and Singapore have augmented testing with widespread quarantine orders for anyone who has been exposed to someone with a confirmed

case, even if no symptoms are evident with those being confined [23]. Contact tracing in several East Asian countries, such as Taiwan and South Korea, has worked well in flattening the curve of cases. The use of phone app technologies to trace contacts in these societies has been effective as compared to the US and EU, but that success may be not simply a result of the technology itself, but of greater tolerance for government and other forms of social tracking in those societies. In other words, cultural difference in attitudes about privacy and community responsibility may have an influence on how Covid-19 spreads [24]. And it is worth pointing out that not only are countries going their own way in developing responses, some are actively working to prevent coordinated action by the few international bodies with standing in the matter –President Trump’s cancelling of WHO funding for domestic political reasons representing an excellent example.

4 DISCUSSION

For our purposes here, the specifics of different responses and policies associated with the pandemic are less important than the fact that these differences are products of cultural, ideological, and political variations among and within nations of the world. Think about the US case as an example. The US political system distributes responsibility for health and public safety largely to states rather than solely to a central national government and has long-standing ideological conflict over the role of the federal government in state affairs. These characteristics combined with both inaction and lack of a clearly articulated and executed national strategy to slow the spread of the virus, have resulted in significant variation in how the pandemic has evolved in different parts of the country. Stated more strongly, it can be argued that the lack of a clear federal strategy in the US has forced the states to “invent the wheel” independently, even to the point of competition between states for access to medical and other resources. Only as the intensity of the crisis eases slightly such that state governments are beginning to think and plan on how to relax protocols have regional groupings of states formed to coordinate action in the absence of decisive federal leadership. In other words, the policies used in reaction to the virus and thus its effects are closely tied to –and partially an outgrowth of –social and political values associated with American society. In short, at both the societal-level and individual-level evidence suggests that although a society’s economic and political institutions play a significant role in managing processes that affect members of that society, those institutions are intertwined with cultural factors that are also important elements in how policies and practices are discussed, debated, and implemented [25].

This should be an important lesson in thinking about and planning for the possibility of contact with alien life (whether intelligent or not). Despite the globalized and pan-human rhetoric that tends to surround SETI research and justifications for the continued funding of SETI-related activities, even if the effects of contact may be global, the interpretations of and responses to contact will not. The tendency to miss this point in quite a bit of SETI literature likely results from the more “globalist” culture prevalent in the scientific community – again reinforcing the localized basis of thinking that tends to shape both conceptualization and action in these matters.

It may be helpful to think of this in terms of a specific scenario. Imagine, for a moment, that tomorrow astronomers working at the Allen Telescope Array determine that they have actually received a signal from an extraterrestrial source

and the signal clearly shows intent and, thus, intelligence on the part of the sender. Among the most obvious questions to arise would be: should we respond? The answer, however, is not obvious, because a response involves risks – particularly if the original message was not directed specifically at Earth and thus the sender is likely not aware of the nature and technological level of life on our planet. As Smith notes, there is a high likelihood that any civilization with which we come in contact is much older and, thus technologically superior to our own [26]. Should we send a message that would reveal the location of Earth to a technologically superior species? And what content should we include if we do? How much should we tell them about our world? Do we want to let them know that we are politically divided and, thus, potentially easy to conquer? Do we inform ETI that there are widespread economic disparities among the people of our world? That we have wars? That we are currently trying to deal with a pandemic (and, therefore, may reveal how fractured and vulnerable we are as a planet or that we are vulnerable to remote hacking)?

It is reasonable to conclude that the answers to these questions would vary in relation to perceived national interest on the parts of diverse governments. If, as seems to be the case, human governments are unable to coordinate a unified response to an imminent global threat such as Covid-19, it seems highly unlikely that they would be able to do so in the face of a more abstract possible threat from a distant alien civilization with which we happened to come into contact. Of course, in the unlikely event that ET were to show up on our doorstep, the threat would appear far less abstract, but this does not mean that nation-states would somehow unite in a common effort to save our world. That may work in movies, but our current situation shows fairly clearly that it is unlikely in reality. There may be some level of coordination, but when perceived national interests appear to be at risk, there is a good chance that said coordination will fail quickly.

As the authors have argued elsewhere, there is the distinct possibility contact with ETI will be viewed as either a threat or an opportunity by governments of nation-states and may be conceived as having extremely high value [8]. This could, for example, lead to efforts to monopolize communication with ETI as a means to gain technological dominance over other nation-states. History tells us that when states perceive something as vital to national interests or national security, they will act in terms of their assumed best interests rather than cooperating with other nation-states. An example of this can be seen clearly in US President Trump's withdrawal of funding from the World Health Organization, which clearly runs contrary to a global and coordinated response to the pandemic (as was highlighted earlier). Of course, this action has generated political conflict as other leaders around the world criticized the US action. Even within normally allied conservative groups in the US, some argued that cutting WHO funding amidst the Covid-19 pandemic was not in US interests, given the organization's central role in helping developing countries to respond to the crisis [27].

5 LESSONS FROM THE PANDEMIC

What is clear already in the Covid-19 pandemic is that in different countries, the virus has spread through populations at various speeds depending on factors such as cultural and behavioral responses in local communities, population density, socio-economic status, average household size, and so on. And "this pattern has led to substantial variation in the preparedness of countries and their responses to the crisis [28]."

Clearly, there are lessons to be learned from the early days of the Coronavirus pandemic for thinking about protocols to help humans in the event of contact with extraterrestrial intelligence (as well as other extraterrestrial life forms such as microorganisms). To conclude, we would like to suggest the following key points as lessons which should guide future thinking about contact with ETI.

- Even if it is determined that ETI poses an existential threat to humanity (or significant parts of humanity) unless social and governmental structures change significantly, a well-coordinated and unified response to either physical or remote contact with ETI is highly unlikely.
- Cultural variation evident in complex and conflicting value systems will play a significant role in how nation-states, as well as groups within nation-states, interpret and respond to contact. This will inevitably lead to disagreement and conflict among humans, which has the potential to destabilize fragile economies and political systems and escalate into violent conflict.
- The very cultural, political, and economic variations that humans display and experience have the potential not only to provide multiple options in responding, but also may work against a successful response. We have seen this in response to the Coronavirus, and it is reasonable to expect a similar situation arising in response to contact with ETI.

In the face of a potential existential threat, unified, coordinated action is immensely important to the chances of a successful outcome. Thus, in military affairs (where existential threats are the norm), unity of command, one commander (whether that is a single person or a group) is essential to maximizing effort. When units have divergent goals, at best they derive no synergy, at worst, they can actually hamper each other's efforts. Thus, in the cornerstone US military doctrine document Joint Publication 1, the first topic covered on how to actually conduct military operations is Unified Action (including Unity of Command) [29]. Thousands of years of warfare have taught the value of unity. This is not just modern; one of Sun Tzu's five principles included unity of command. Counter examples (of which there are too many to mention in detail here) where the lack of unified effort was catastrophic include the near-total loss of the Roman army to Hannibal at the battle of Cannae (216 BCE) due in part to different Roman consuls commanding the Army on alternating days [30]. In the recent past a good example, while not completely disastrous, includes different countries within a war coalition having contrary rules of engagement and national aims, resulting in confusion and inefficiency (at best) [31]. Thus across the most critical of human endeavors, the value of unity of effort is essential, but cultural, political, and economic differences among groups can mitigate against achieving that unity.

This is not to say that there is no hope for unified effort. And it is important to recognize that diversity is generally a strength in human society to be tapped when facing challenging situations; but in the face of a global threat it is also important to recognize that diversity can work against creating a coordinated effort unless factors such as good leadership and a well-conceived and planned protocol for assessing and dealing with risk are already in place – ahead of the point of a crisis. In fits and starts, countries have worked together both within and outside of crisis scenarios. The United Nations is the most obvious but only partially successful example. NATO and other military coalitions, particularly in war, have been fairly successful in coordinating action when the stakes are clear. On

more practical day-to-day affairs, economic/trade/communications/transportation treaties and agreements perform quite well at coordinating and reconciling national interests. For our purposes here, international agreements with teeth are likely to be the result of significant education and public mobilization efforts over a long term combined with select “early adopter” countries leading the effort officially. This is precisely what is needed now as we begin to seriously contemplate the possibility of contact with extraterrestrial life. And this needs to happen before contact occurs, or we are very likely to find ourselves in a situation similar to the current pandemic in which an unexpected external threat suddenly puts the world into a poorly coordinated and variably successful situation as diverse countries and groups interpret and respond to an event that has the potential to rise to the level of global existential threat.

A significant step that needs to be taken in this direction can

begin with the SETI scientific community. Rather than working from an assumption that humans live and operate within a civilization, SETI scholars need to develop a more nuanced representation of human life on our own planet and generate a discourse surrounding SETI that recognizes human diversity. This also should help us in recognizing that ETI may be just as diverse as we are, or even more so. If we take this step forward at a conceptual level, we can begin to develop protocols for contact that assume diversity of cultures, interpretations, and responses to contact. When thinking about how humanity might respond to contact with ETI, we should build-in recognition of and thoughtful strategies for dealing with cultural, economic, and political diversity and recognize that there is a high potential for contact to stimulate increased conflict and disagreement among human groups – again as is evident in the Coronavirus pandemic – rather than to unify humanity in response to a real or perceived global threat.

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WATER AND AIR CONSUMPTION ABOARD INTERSTELLAR ARKS

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The architecture of a large interstellar spaceship, which is capable of serving as a living environment for a population over many generations, is mainly dictated by the needs of said population in terms of food, water and breathable gases. These resources cannot be stored for the entire duration of a journey that goes on for several centuries, so they must be produced in situ. In order to determine the quantities necessary for the survival of the population, it is imperative to precisely estimate their needs. In this article, we focus on accurate simulations of the water and air (oxygen) requirements for any type of population in order to be able to provide precise constraints on the overall architecture of an interstellar ark (the requirements in terms of food having already been studied in a previous publication). We upgrade our agent-based, numerical, Monte Carlo code HERITAGE to include human physiological needs. Our simulations show that, for a crew of about 1100 crew members (each characterized with individual anthropometric and biological data), 1.8×10^8 litres of oxygen are annually required, together with 1.1×10^6 litres of water. Those results do not account for oxygen and water used in growing plants, but they give us an insight of how much resources are needed in the spaceship. We also review the best methods for generating water from waste gases (namely carbon dioxide and dihydrogen) and how such systems could complement the oxygen-supplying biospheres inside multi-generational spaceships to form a closed and controlled environment.

Keywords: Long-duration mission, Multi-generational space voyage, Space exploration, Space resource

1 INTRODUCTION

1.1 Space Colonies

In order to prepare for a long-term mission in an environment where resources are scarce, it is necessary to plan and budget for the equipment to bring, to build on site and to recycle. If we take the real example of the French commercial ship *Clairon et Reine*, a brig which regularly travelled from Marseille (France) to Smyrna (Turkey) between 1827 and 1836, we can study how the rationing in food was important and precise in order to carry out long sea crossings [1]. According to the ship's documents found in 1973, each of the ~ 10 sailors obtained a ration of nearly 4200 daily kilocalories in bread, meat, fish, vegetables and cereals, which matches their intense physical activity level. Thousands of litres of liquids (mainly alcohol and water) were loaded on board before each departure, so that month-long trips could be achieved [2]. This represents several tens of tonnes of food which tended to spoil after a few weeks. Now, let us compare this situation to space travels, where breathable air becomes a valuable resource that must be taken into account in the equation. In addition, it will not be possible to fish in the vacuum of space, so food cannot be easily replenished. Storing enough food, water and nutriment, together with a breathable mixture of gases, represents a challenge. First it will require physical space and add mass to the space shuttle or spaceship, which drives higher costs (larger ships, stronger propulsion systems). Second, water and food will eventually spoil in time despite the best industrial methods for food preservation and

storage [3, 4]. These problems are at the centre of contemporary thinking for the human exploration and colonization of Mars [5, 6, 7, 8, 9], but also for interstellar journeys to nearby exoplanets [10, 11, 12, 13].

Sending humans to exo-worlds situated tens of parsecs away from the Earth is a rather complex project, since it calls for travelling in deep space for hundreds of years with subluminal propulsion systems. The technological complexity of such a giant spaceship has been highlighted by many authors [10, 14, 15], but it is universally recognized that the human aspect of the mission is even more complex. Multi-generational spaceships are probably the best option we have since population resources consumption over time can be modelled with great precision [16]. These generation ships rely on the principle that the population aboard will live, procreate, teach the new generation, and die, allowing the offspring to continue the journey. Inside the vessel, a closed ecological system would artificially reproduce Earth-like conditions, landscapes and flora. The population of a space ark should not be considered as a unique crew with a distinct goal, but rather as families and communities living out normal, small-town lives in the world ship [17]. However, in order to continue the journey, their basic physiological needs must be fulfilled.

Among the several solutions that have been postulated to solve the issue of the inevitable depletion of food, water and breathable gas supplies, the most convincing one is the production of resources within the spaceship. This can be achieved

by either recycling wastes, by growing food and plants in biospheres, or by using chemical reactions to transform non-breathable gases to oxygen. But how much food, water and oxygen is needed to ensure that the crew will have enough resources to live a prosperous life? Precise quantitative estimations have been achieved in the case of short duration spaceflights with a limited crew (see, e.g., [18]) but never in the case of long-duration interstellar travels with a dynamic population, which is the goal of this paper. We addressed the question of food production and requirements in a previous publication [13]. We now turn our attention and our numerical simulation tool HERITAGE towards the issue of water and air consumption aboard an interstellar spaceship whose crew consists of a multi-generational population. In the following, we will present the latest upgrades of our agent-based code that were necessary to properly compute the annual basal oxygen consumption and the estimated water requirements of the population. Then, we will review the various methods of replenishing the spaceship with pure water and air before concluding on the importance of planning for a long-duration voyage.

2 UPGRADING HERITAGE

2.1 Overview of the agent based Monte Carlo code

The numerical code HERITAGE is a computer program that was created to follow the evolution of a multi-generational population within a closed environment with limited resources and neither immigration nor emigration. HERITAGE has been applied to interstellar space travels but can very well be applied to local (Earth) situations such as an isolated tribe in the jungle, an island or a Mars colony experiment such as the Mars-500 project [8] or the Hawaii - Space Exploration Analog and Simulation (HI-SEAS) [19]. The uniqueness of the code comes from the fact that it is an agent based tool. Each crew member is fully simulated using a specific blueprint (a C++ language class) that includes the most important biologic and anthropometric data that are needed to characterize a real human: age, gender, weight, height, genome, fertility, etc. The biological factors are time-dependent and follow biological and physical laws so that the population can grow old, reproduce and die in a biologically realistic way. This allows us to model a real population with mixed generations and heterogeneous characteristics rather than populations with clearly separated generations, as what is usually done in population genetics studies [20, 21]. HERITAGE is also a Monte Carlo code, which means that each event happening in the spaceship (reproduction, accidents, genetic processes, and so on) are the result of random draws that follow mathematical laws. This means that the code can test all possible outcomes of an event by performing successive draws. The code must be lopped several times (at least one hundred times, see [13]) to have statistically significant results and determine the most probable outcomes. The results of the simulations are then averaged over hundreds of loops that, depending on the number of crew members, can take hours to days to complete.

The code has been extensively described in the previous papers of the HERITAGE project [22, 23, 13]. In the following, we will only review the new features that are necessary to determine air and water consumption aboard a closed environment.

2.2 Equations for air consumption

The daily quantity of air needed by a human under minimal psychological and physiologic stress, and at an ambient tem-

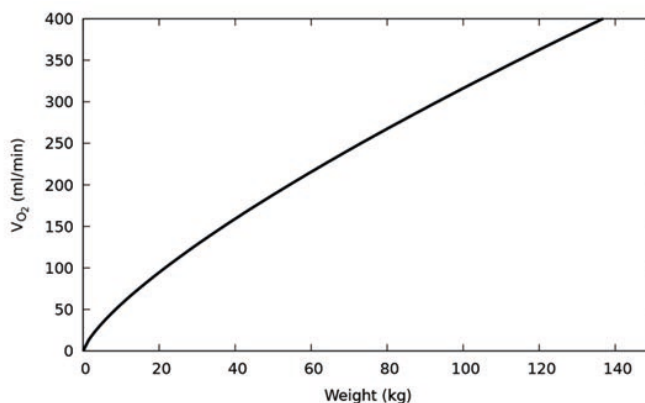


Fig.1 Plot of the Brody's equation.

perature of between 20 and 26.6°C, has been derived thanks to indirect calorimetry during clinical experiments [24, 25]. Surprisingly, this quantity depends only marginally on the sex and height of the test subject but more strongly on its weight. Indeed, there is a strong correlation between the body size and metabolic rate of mammals [26]. Based on clinical observations, an equation was derived to express the basal oxygen consumption (V_{O_2}) as a function of the subject weight w [27, 24]:

$$V_{O_2} = 10w^{\frac{3}{4}} \quad (1)$$

in millilitre per minute. This equation is known as Brody's equation, whose representation can be found in Fig. 1. It is a continuous function that can be used as a good proxy for human oxygen needs in stress-free situations. By volume, dry air (> 10% humidity) contains 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide, and small amounts of other gases [28]. Air also contains a variable amount of water vapour, on average around 1% at sea level, and 0.4% over the entire atmosphere. From Brody's equation, it is thus possible to estimate the basal oxygen consumption of a whole population (if the weight of each individual is known) and then derive the related volume of accompanying gases.

2.3 Equations for water consumption

Water is the largest constituent of the human body and can be viewed as the most essential nutrient. It contributes to the global health of humans and also accounts for a large fraction of their body weight. Ingesting insufficient daily water doses leads to dehydration and volume depletion [29], while too much water leads to over-hydration and hyponatremia [30]. In order to avoid those life-threatening conditions, an appropriate amount of water must be consumed per day. It is recognized that a minimum of one litre per day is necessary to survive [31], but if we want to move away from this scarcity assumption, it becomes less trivial to properly assess the amount of water that is required to maintain a healthy body. There are at least five equations used by clinicians to determine water requirements. Studies have pointed out that those five Estimated Water Requirements (EWR) equations are strongly correlated but do not necessarily agree with each other [32]. To determine the best equation, the calculated EWR results were compared to measurements from the total water intake (from food and beverages) from a representative sample of the United State population. The strongest agreement between the total water intake and the estimated water requirements is found in the case of the equation issued by

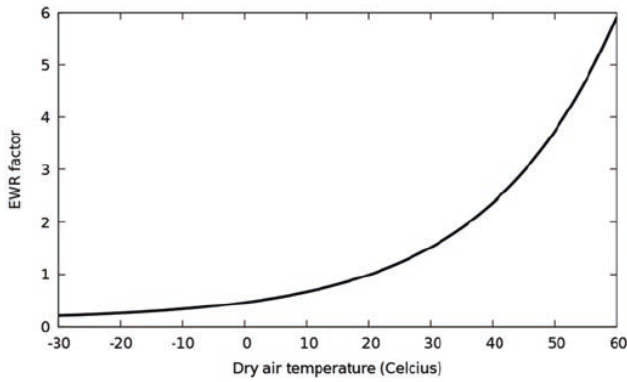


Fig.2 Correction factor applied to the EWR as a function of dry air temperature aboard the spaceship. The model is normalized to unity at a nominal temperature slightly below 20°C and detailed in the text.

the NRC (National Research Council) [32]:

$$EWR_{\text{Q}} = 354 - (6.91 \times A) + (9.36 \times W \times PAL) - (726 \times H \times PAL) \quad (2)$$

$$EWR_{\text{G}} = 662 - (9.53 \times A) + (15.91 \times W \times PAL) - (540 \times H \times PAL) \quad (3)$$

with W the weight in kilograms, H the height in meters, A the age in years, and the EWR in millilitre per day. The acronym PAL stands for Physical Activity Level and is used to express

a person's daily physical activity as a quantitative value. Those equations are based on the basal metabolic rate of individuals, such as already computed by HERITAGE (see [13]). They have the advantage of accounting for the body mass, body height, age, gender and physical activity level of the subject. All those parameters are already included in HERITAGE from the previous upgrade. We thus simply included those equations into our code to estimate the daily water requirements.

It must be noted that the estimated water requirements are very temperature-sensitive: EWR increases with ambient temperature as a result of sweating. The United States Army Research Institute of Environmental Medicine has developed an empirical model that includes an equation to predict sweating rate during work [33, 34]. The model is valid for dry air temperatures that range between 15 and 40°C and accounts for four different physical activity levels. The model has an exponential dependency on temperature with proportional rate growths (see [31]). We used the model to numerically determine a temperature-dependent correction factor f_{EWR} to apply to the EWR value obtained with Eqs. 2 and 3:

$$f_{\text{EWR}} = a - \frac{b}{c} \times (1 - \exp(-c \times T)) \quad (4)$$

with T the dry air temperature in Celsius degrees, $a = 0.462$, $b = 0.016$ and $c = 0.048$. This correction factor must be multiplied to the EWR to account for the temperature-dependent daily dose of water needed by each crew member. A visual representation of f_{EWR} is shown in Fig. 2.

The correction factor has been normalized to an ambient dry air temperature slightly below 20°C and a numerical fit al-

TABLE 1: Input parameters of the simulation*

Parameters	Values	Units
Number of space voyages to simulate	100	–
Duration of the interstellar travel	600	years
Colony ship capacity	1200	humans
Overpopulation threshold	0.9	fraction
Inclusion of Adaptive Social Engineering Principles (0 = no, 1 = yes)	1	–
Genetically realistic initial population (0 = no, 1 = yes)	1	–
Number of initial women	250	humans
Number of initial men	250	humans
Age of the initial women	30 ± 5	years
Age of the initial men	30 ± 5	years
Number of children per woman	2 ± 0.5	humans
Twinning rate	0.015	fraction
Life expectancy for women	85 ± 5	years
Life expectancy for men	79 ± 5	years
Mean age of menopause	45	years
Start of permitted procreation	18	years
End of permitted procreation	40	years
Initial consanguinity	0	fraction
Allowed consanguinity	0	fraction
Life reduction due to consanguinity	0.5	fraction
Chaotic element of any human expedition	0.001	fraction

*The $\mu \pm \sigma$ values shown for certain parameters indicate that the code needs a mean (μ) and a standard deviation value (σ) to sample a number from a normal (Gaussian) distribution.

lowed us to extend the temperature range from negative values up to more than 60°C. Nevertheless, the HERITAGE code will emit a warning message whenever the temperature within the spaceship is below or above the nominal temperature range fixed by [33, 34], so that the user will know that the results are subject to larger uncertainties. The annual dry air temperature aboard the spaceship is now input data (similarly to the year-by-year catastrophe risks and equivalent doses of cosmic ray radiation) that can be fixed by the user. Note that for climate control, a typical ambient temperature range is anywhere between 15 and 25°C. The human body, dressed appropriately, can survive for a year under extreme conditions ranging from -60 to +50°C in dry air conditions and with regular access to water at cooler temperatures in the latter case [35]. Above and below those limits, the crew members are killed by the program. Finally, effects of extreme temperatures on the human biological functions, such as fertility or blood flow [36, 37], are rather complex to model and are not included in HERITAGE at this point.

3 SIMULATIONS

Now that the code has been upgraded to account for air (oxygen) and water consumption, we can run a complete simulation to obtain the annual requirements in terms of food, water and air. To do so, we set up HERITAGE according to the parameters listed in Table 1. We simulate a relatively short space travel (600 year long) with a worldship of modest size: a maximum of 1200 crew members can live inside the vessel but we impose a security threshold of 90% of that value to prevent overpopulation and resource depletion. We include adaptive social engineering principles that is a self-regulation of the population whenever the overpopulation threshold is reached. No inbreeding is tolerated on board (up to first cousins once removed or half-first cousins) and the procreation window is wide: from 18 to 40 years old. The crew is expected to be rather inactive when young (< 18 years old), moderately active in their age 18 – 24, vigorously active between 25 and 50, moderately active up to 70 years old and sedentary for the rest of their life. We postulate that the radiation shield of the interstellar ark is very efficient so that the annual equivalent dose of cosmic ray radiation never exceeds 2 millisieverts in deep space (i.e., beyond the protective limits of the Sun and of the star around which is orbiting the targeted exoplanet). This prevents any serious risks of neo-mutations, cancers and genetic malformations. The initial crew is gender-balanced and older than in our previous simulations: 30 years old on average with a standard deviation of 5. This means that a few crew members are older than 40 years old and some are younger than 20 at the beginning of the mission. To move away from the scarcity paradigm (i.e., imposing the minimal viable population of initial settlers at year 0, which is of the order of 100, see [23]), we choose a departing population of 500 humans. We will discuss the socio-demographic importance of the initial population age and number in another publication. We set up a chaotic factor that can randomly kill any crew member for unexpected reasons (deadly accident, premature death, serious illness, etc.) to 0.1% per year. Finally, the dry air temperature aboard is stochastically oscillating between 18 and 21°C and we set up three incidents along the course of the multi-generational ark at years 191 (20% casualties), 350 (30% casualties) and 490 (17% casualties). The casualty percentage rates are chosen to mimic large-scale catastrophes and diseases, such as the 14th century Black Death (~30% of the European population died, [38]) or the 1918–1919 Spanish flu pandemics (~22% of the Samoan population died, [39])

The results of the simulations are shown in Fig. 3. The top-

left panel shows the evolution of the population within the spacecraft. From 500 at the beginning of the interstellar travel, the crew quickly increases up to the security threshold. At this point, the population number is subject to strong variations as the crew is dominated by demographic echelons clustered in discrete age groups. With time, this clustering gradually disappears and a stable population level with people of many different ages develops. The three catastrophes have little impact onto the resilience of the crew and the population quickly returns to the stable population level after the lethal events. The rate of mission success is precisely 100% in this case. The top-right panel of Fig. 3 shows the total energy expenditure in kilo-calories per year. On average, there is a need for ~ 109 kcal per year to maintain ideal body weight. Following our investigations presented in [13], this total energy expenditure drives a surface for geponic agriculture of about 2 square kilometres of farmland for a balanced diet (fruits, vegetables, meat and fish, dairy and starch). The use of hydroponic and/or aeroponic agricultures could help to reduce this surface by a factor of two. The bottom-left figure presents the basal oxygen consumption in litres per year. We see that about 1.8×10^8 litres of oxygen are annually required to keep the crew alive. At the spaceship ambient dry air temperature, considering a pressure of one atmosphere, this represents a volume¹ of $1.8 \times 10^5 \text{ m}^3$ ($2.4 \times 10^5 \text{ kg}$). If we account for nitrogen among the breathable gases, at a fraction of 78.09% of the air composition, this means that an additional amount of 6.7×10^8 litres of nitrogen is needed inside the vessel, which corresponds² to $\sim 6.7 \times 10^5 \text{ m}^3$ ($7.7 \times 10^5 \text{ kg}$). In total, the spaceship must have a volume of about 10^6 m^3 just to store the required breathable gases (nitrogen and oxygen) at 21°C and at a pressure of one atmosphere for a full year. Considering the simplest geometry for such spaceship (a cylinder), this represents a structural length longer than 350 m for a fixed radius of 30 m. Storing a fraction of the gases in pressurized tanks would help to drastically decrease such architectural constraints. The breathable gases could then be released inside the vessel according to the monitored needs of the crew. In addition, it is not necessary to keep enough gases for a full year. Day-to-day oxygen and nitrogen production aboard must participate actively in the renewal of the breathable atmosphere (see Sect. 4.1). Finally, the bottom-right panel of Fig. 3 presents the estimated water requirements in litres per year. There is an annual need of 1.1×10^6 litres of water to hydrate the population. Of course, this amount of water does not include the volume required by the biosphere (plants, animals, insects, bacteria...) inside the ark to survive. It gives us a lower limit solely based on human needs. This quantity represents a volume of 1100 m^3 of water ($1.1 \times 10^6 \text{ kg}$), or a cylinder 35.4 m in length and 3 m in radius. This is a much smaller volume than what is required by breathable gases requirements; water could be stored in containers that are fixed on the vessel's flanks, minimizing the loss of space inside the spacecraft. Due to the coldness of the interstellar atomic and molecular media ($\leq -173.15^\circ\text{C}$, [40]), water stored outside the spaceship would freeze (no need for active cooling in deep space) and could be used as an ice shield against interstellar debris. Pathogens would not proliferate at those temperatures and sterilizing water is a known and easy process. In principle, collecting the required amounts of water from Solar System sources could be achieved well before the mission even begins but, from cost-

¹ 1 litre of oxygen gas represents a volume of 10^{-3} m^3 and a mass of 1.309 g at 21°C and 1 atm.

² 1 litre of nitrogen gas represents a volume of 10^{-3} m^3 and a mass of 1.155 g at 21°C and 1 atm.

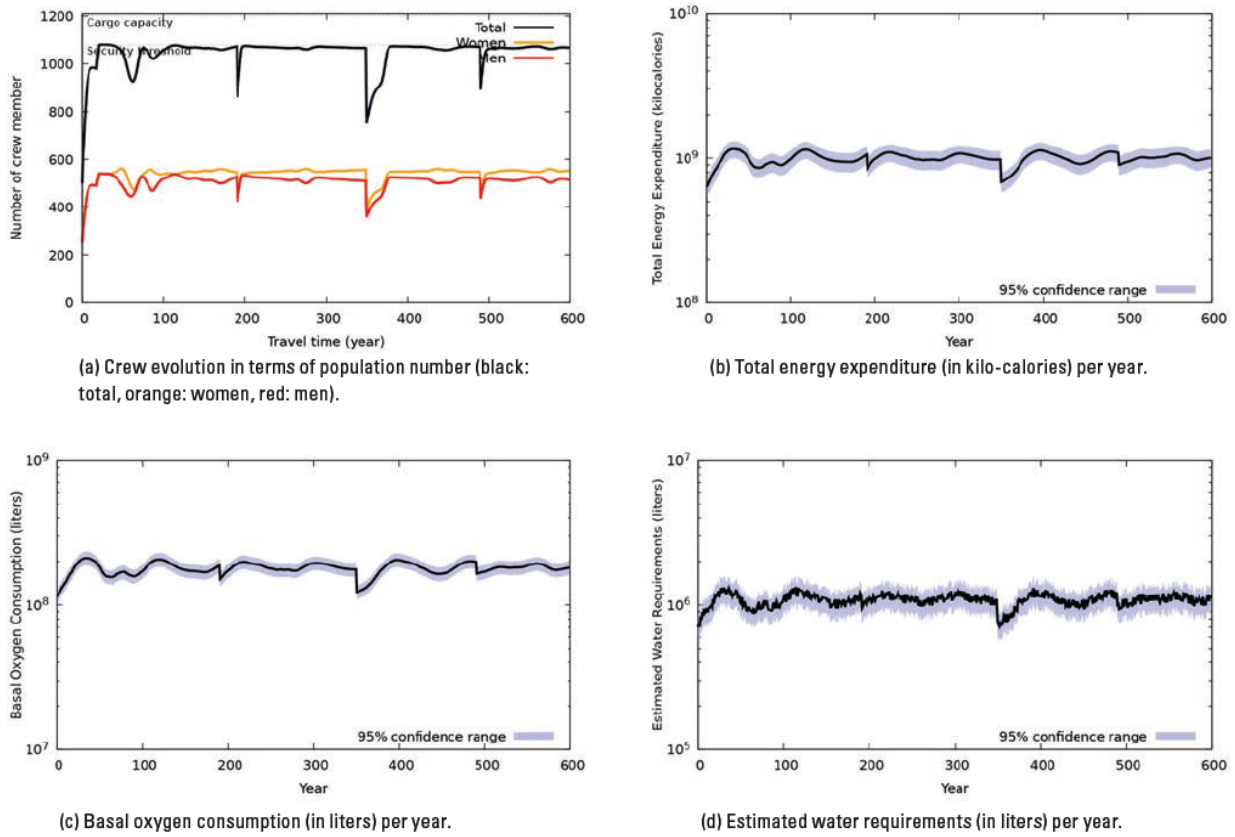


Fig.3 HERITAGE results for a 600 years-long interstellar voyage under the conditions described in the text. The supplemental noise seen in the estimated water requirements is due to the random fluctuations of the dry air temperature aboard the spaceship.

wise and security reasons, it would be preferable to obtain new and fresh water during the journey. The question of how to renew the water supply will be discussed in Sect. 4.2.

4 PRODUCING AIR AND WATER RESOURCES IN SPACE

Our HERITAGE simulations have proven that tremendous annual amounts of oxygen and water are required to keep the crew alive during centuries-long deep space travels. It is not a viable option to store all the necessary resources at the beginning of the voyage since the quality of liquid water would likely deteriorate with time. Microbial cells (pathogenic bacteria such as, e.g., legionella) would ultimately grow and induce pathogenic properties. Excessive growth of bacteria in drinking water leads to hygienic, aesthetic and operational problems [41]. In addition, the required volumes to store millions of litres of water and billions of cubic meters of breathable gases would induce disproportionate costs that could affect the overall feasibility of ark-like projects. For those reasons, in situ recycling and production of fresh air, water and food are necessary [13].

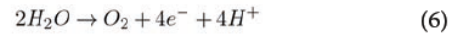
4.1 How to recycle and produce breathable gases?

The most convincing and accurate examples that we have concerning the production of breathable gases in space are the Mir and ISS space stations. Inside those orbiting habitats, large scale plant photosynthesis is not feasible to produce enough oxygen so they rely on several methods to generate breathable gases: pressurized oxygen tanks, oxygen generators and solid fuel ox-

ygen generators. These systems are not perfectly efficient and losses are compensated by deliveries from Earth. Of course, the delivery of oxygen to an interstellar spaceship is not realistic, but nothing prevents the crew from storing oxygen in pressurized tanks in case of a disaster. To provide a continuous flow of oxygen, generators such as the Russian-made Elektron-VM [42, 43] and the United States Environmental Control and Life Support System (ECLSS, [44, 45]) are used. The oxygen generators option relies on water electrolysis that splits H_2O molecules into hydrogen gas and oxygen gas such as:



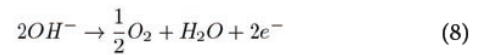
at the cathode and:



at the anode when the half reactions are balanced with acid. In the case of a balance with a base, the reactions become:



at the cathode and:



at the anode. Combining either half reaction pair yields the same overall decomposition of water into oxygen and hydrogen:



The electricity is generated by the station's solar panels and supplied to the oxygen generators through the station's power grid [46]. Water is essentially provided from Earth by space shuttles, which make oxygen generators such as Elektron-VM and ECLSS less reliable in case of water shortage. The last method to produce breathable gases uses chemical reactions. Solid fuel oxygen generators consist of canisters that contain a mixture of powdered sodium chlorate (NaClO_3) and iron (Fe) powder. The ignition of the iron powder provides the heat energy required to break down the sodium chlorate into sodium chloride and oxygen gas (plus residual iron oxide) such as:



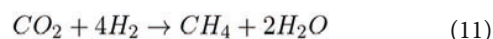
One kilogram of mixture is enough to provide oxygen for 6.5 man-hours [47, 48, 49, 50]. Chemical oxygen generators are the most used methods to supply oxygen in confined spaces, especially because of their long shelf life and reliability. Nevertheless, all the three technologies require resources that are not effortlessly accessible in deep space. Recycling breathable gases is necessary but not easily achievable, even in space shuttles and space stations. Experiments involving organic compounds [51, 52] or microalgae [53, 54, 55] to recycle carbon dioxide are under study but they are not expected to be 100% efficient. The only way to provide enough breathable gases and recycle gas wastes is to mimic the Earth system: growing plants in space. This is a challenging task but the recent success of the Chang'e 4 lunar lander in January 2019 is paving the way towards more and more complex biosphere experiments. The Chinese mission carried a 3 kg sealed biosphere-like box with seeds and insect eggs to test whether plants and insects could hatch and grow together in synergy. It successfully achieved the sprout of cotton seed (and, maybe, of rapeseed and potato seeds, but this has not been confirmed yet) within nine days, before a failure of the temperature system [56]. Larger biosphere experiments, such as Biosphere II, are trying to recreate a viable ecosystem inside a huge closed dome that could very well be representative of a spacecraft [57, 5, 6, 7]. This option is the only realistic one to consistently provide enough breathable gases to multi-generational crews, recycle carbon dioxide and other by-products of life aboard a closed system, and create a pleasant living and working environment for the crew. However, this potential solution must be explored carefully since the carbon dioxide content of the air is low; hence it might require a significant extra mass of carbon. In addition, it is extremely difficult to calculate how the efficiency works with such complicated networks, since some carbon dioxide will be taken up by the plants for photosynthesis. Large scale experiments, such as Biosphere II, are therefore fundamental to the preparation of interstellar arks.

4.2 Where to find water in deep space?

The problem of renewing water in space is even more complex than that of creating oxygen in a closed environment. The Solar system is full of small icy bodies (comets and asteroids) that could be collected prior to the mission or even during the spaceflight to restore the water tanks level after purification of the melted ice. Harvesting water in the Solar system before the launch of the space ark might be a good option since it can be done during the construction time of the spaceship. However, as we already stated it, it is dangerous to travel with all the water stored for the mission. In case of a catastrophe that would destroy part of the reserves, this would mean the end of the mission. It is then necessary to collect additional water on the course to the exoplanet. But, is this really an option? The closest

asteroid belt is the Main Belt. It is estimated to contain millions of objects and is located between the orbits of Mars and Jupiter ($\sim 2\text{--}3$ astronomical units, au, from the Sun). Further away are Trojan asteroids, rocky/icy bodies that are a separate group of asteroids lying outside the main asteroid belt and sharing an orbit with Jupiter ($\sim 5\text{--}6$ au). Several comets and ice-coated irregular satellites of the giant planets are situated shortly after the Trojan asteroids, up to the Neptune Trojans at ~ 30 au. At larger distances from the Sun, Kuiper belt objects fill the space up to ~ 55 au. Most of the aforementioned asteroids are situated along (or close) to the planet's orbital plane [58]. This means that any interstellar travel whose direction does not lie close to the Solar System ecliptic plane is less likely to encounter asteroid that could be harvested to restore water levels (at least up to 55 au). In addition to the inherent risks of boarding a fast moving³ space rock, the chances to encounter enough asteroids along the spaceship's trajectory within the Solar System is rather low if the ship's path deviates from the ecliptic. The only true potential reservoir of frozen water that lies "close" to the Sun is the Oort cloud. The Oort cloud is a large hypothetical spherical reservoir of comets that surrounds the Solar system at distances between 20000 and > 100000 au [62]. The outer envelope could be the source of most long-lived comets and be an ideal target for water replenishment if the risk is worth it. Finally, in the deep interstellar space, the number density of comets and asteroids that could be used to extract water is so low ($1.4 \times 10^{-4} \text{ au}^{-3}$ at a 90% confidence limit, [63]) that such an option could be safely discarded.

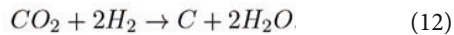
We established that extracting water from comets and asteroids during the spaceship course is not a viable option. Is recycling water from humans, plants and industrial activities within the spaceship feasible? Aboard the ISS there are two water recovery systems, one that processes water vapour from the atmosphere (the water is then fed to electrolysis oxygen generators) and one that processes water vapour collected from the atmosphere and urine into water that is intended for drinking. However, they are not 100% efficient since some water is lost due to small amounts of unusable brine produced by the recycling systems, water consumption by the oxygen generators, airlocks leaks that take humidity with them, and a few more. Even with a 95% efficient system, such as the NASA's Vapor Compression Distillation experiment [64], the amount of water that is lost per year is non-negligible and requires filling the reserves with fresh water. This demonstration has the corollary that some water must be created within the ship in addition to the water recovered from the recycling systems. To do so, we can rely on chemical reactions. In particular, the Sabatier process could be used to produce methane and water. To do so, the methodology relies on the reaction of hydrogen with carbon dioxide at elevated temperatures (optimally $300\text{--}400^\circ\text{C}$) and pressures in the presence of a nickel catalyst [65, 66, 9]. The chemical exothermic process is such as:



A very interesting by-product of the Sabatier reaction is the production of methane that could be very well used as a propellant for the spaceship. In addition, this process would recycle the human production of carbon dioxide to produce water, that in turn could be used to water the plants and create

³ The average orbital speed of a main-belt asteroid is 17.9 km.s^{-1} , the orbital speed of Ceres [59]. Ceres has a pretty typical orbit and makes up a third of the Belt by mass [60, 61].

a complete loop. Along the same line of thoughts, the Bosch reaction is under study to complement the Sabatier reaction to maximize water production aboard the ISS or during future Martian colonies [9]. The overall reaction is:



This reaction requires the introduction of iron as a catalyst and requires a temperature range of 530 – 730°C [67], which is substantially higher than the Sabatier process. Yet, similarly to the first chemical method, the Bosch reaction would also allow for a completely closed hydrogen and oxygen cycle within the biosphere. The by-product of this reaction is the production of carbon that could be used for manufacturing, but the production of elemental carbon tends to foul the catalyst's surface, which is detrimental to the reaction's efficiency.

4.3 Life support systems, virtual habitat models and HERITAGE

The ECLSS aboard the ISS is part of the more general class of life support system (LSS). The goal of any LSS is to create and manage a viable environment with sufficient breathable gases, water and food, but also to maintain human-adapted temperature and pressure conditions. Another task of a LSS is to manage waste and recycle unnecessary material. The ECLSS is crucial for the survivability of the ISS crew and it is easy to foresee that a similar (yet at larger scale) situation would apply in the case of generation ships. LSS are well adapted for astronaut crews that are, on average, anthropometrically similar. In the case of the ECLSS, the human baseline values and assumptions are such: a typical crew member has a mass ranging from a 95th percentile American male, with a total body mass of 99 kg, to a 5th percentile Japanese female, with a total mass of 53 kg [68]. Despite the use of similar equations for the basal metabolic rate and water consumption than in this paper, the ECLSS assumptions about the crew body mass and metabolic rate are only valid for humans older than 19 years. The water/air consumption and wastes of the same standard crew member with a fixed respiratory quotient at a fixed ambient temperature are averaged, and the physical activity levels are planned over a standard workweek [69]. No children nor elder crew members are accounted for in the human model of the ECLSS. Those strong assumptions are perfectly valid for the ISS case, where only trained astronauts are likely to go, but the assumptions must be corrected in the case of an interstellar ark. Our HERITAGE code is certainly not as efficient as the ECLSS model in the case of a daily estimation of the human needs. Most of the biological functions included in the code are based on medical data that are year-dependent, not day-dependent. For this reason, HERITAGE is not likely to replace a LSS. However, our code has the dual benefit of being adapted to the yearly consumption of any type of population and it is a dynamical code that reacts to changes in temperature, cosmic ray radiation doses, population size variations, etc.

HERITAGE shares more comparative points with virtual habitat models. In particular, the V-HAB model developed by

the Exploration Group in Munich [70, 71, 72] includes a dynamic representation of the crew to be integrated in any LSS. The human model includes a much more sophisticated representation of the human body (lungs, heart, kidneys, fluids ...) and very precise estimations of the water, food and breathable gases intake can be achieved. The V-HAB model works very well when compared to ISS data and can be used to prepare a Mars colony with reliable numbers. Nevertheless, the human model in V-HAB remains static, in the sense that only standardized, active, male adults can be modelled [72]. HERITAGE accounts for gender, age, size, weight and genetic diversity. This makes HERITAGE a valuable and complementary tool to LSS and virtual habitat models to obtain precise (at a year time-scale) quantitative values of the human needs in terms of food, water and breathable gases, accounting for a dynamical population that is truly representative of an off-world colony.

5 CONCLUSIONS

We have developed the HERITAGE code to include water and oxygen consumption aboard multi-generational interstellar spaceship. The code now estimates the annual requirements in terms of water and oxygen volumes that a heterogeneous population would need to live comfortably, accounting for various physical activity levels, body shapes and ambient dry air temperatures. The results of a simulation where about 1100 crew members are numerically investigated shows that about 1.8×10^8 litres of oxygen are annually required to keep the crew alive, together with $\sim 10^6$ litres of water. Those results do not account for oxygen and water used in growing plants, but they give us an insight of how much resources are needed in the spaceship. This, in turns, help us to determine the architectural constraints of such an enterprise.

In order to narrow down the possibilities to restore the levels of breathable gases and water, we undertook a concise review of the methods for recycling and producing air and water in space. The most convincing methods rely on photosynthesis aboard the spaceship and chemical reactions to maintain a closed loop for water and air. Humans (and animals and insects) would inhale air and exhale carbon dioxide. This carbon dioxide will in turn be partially recycled by the plants from the biosphere, and partially used to feed the Sabatier and Bosch chemical reactors to produce water. Water will be used to hydrate humans and water the plants. The by-products of the chemical reactors could be then used as engine fuel or raw material for industries. This first order scheme is of course too simplistic as such, but it gives us a direction of study to really get a stable biosphere.

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HABITABILITY OF M DWARFS:

a problem for the traditional SETI

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We consider some implications of the much-discussed circumstellar habitable zones around M-dwarf stars for the conventionally understood radio SETI. We argue that the flaring nature of these stars would further adversely impact local development of radio communication and that, therefore, their circumstellar habitable zones should be preferentially studied by other methods. This is a clear example of how diversity of astrobiological habitats is introducing contingency into the cultural evolution, thus undermining the universality of cultural convergence as one of the major premises of the traditional SETI, and of how specifics of the physical environment strongly shape cultural evolution taken in the broadest, most inclusive sense.

Keywords: SETI, Covid-19, Pandemic, Risk, Cultural diversity

1 INTRODUCTION

There has been a dramatic surge of interest in planetary habitability following discovery of large number of small, Earth-sized planets in exoplanetary systems of red dwarf stars such as Proxima Centauri [1], Kepler 42 [2, 3], or TRAPPIST-1 [4]. Gradually emerging consensus suggests that, just as M-dwarfs dominate with more than 70% in any representative sample of the Main Sequence stars [5], planets around M-dwarfs dominate the overall tally of planets in the Galaxy. The fact that M-dwarfs might not be easy to find and study in biased, usually flux-limited surveys (Fig.1), should not occlude this ground truth: any general statement concerning habitability, biosignatures, technosignatures, etc. should be conditionalized on the statistical predominance of red dwarf stars.

This includes the halo population of very old red dwarfs as well [6]. Obviously, consequences for astrobiology are dramatic: habitability of exoplanets and exomoons around red dwarfs has become one of the most discussed issues in recent astrobiological research [7-15]. While all results are necessarily very tentative as of this writing, there is a growing trend of accepting planets around red dwarfs as legitimate part of the overall set of habitable planets in the Galaxy.

Even modern studies on the rate of habitable planetary formation throughout the Milky Way history are nowadays led to separate red dwarf planetary systems from the rest of the Main Sequence stars [16, 17]. Including the former leads to significantly different values of such crucial quantities as the median age of habitable planets in the Milky Way. In fact, the emerging position seems to be that an *average* habitable planet should be

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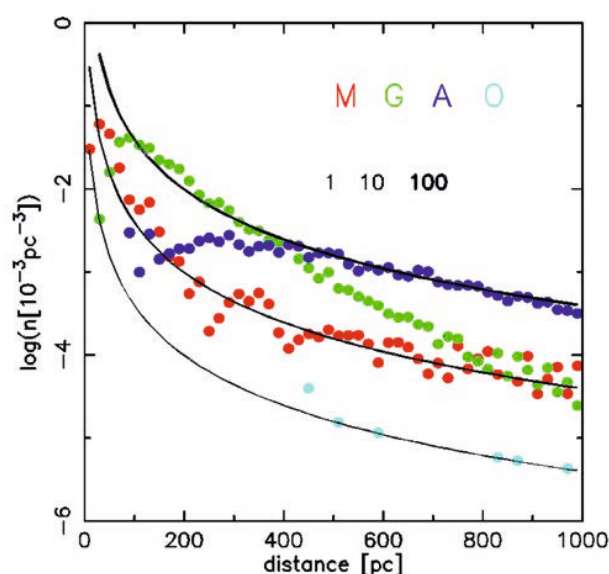


Fig.1 The average density of stars with distance. Stars are counted in spherical shells of 20 pc width. The spectral types are color-coded as designated while the black lines of different width represent the density for the number of stars at the shell at the given distance, as designated in the plot. The data was queried per spectral type from the SIMBAD database on October 12, 2019.

located around a red dwarf star, prompting a natural question why are we – as per an anthropic selection effect – not located around one as well [18]. Even if we conclude that the observers of our kind are not vanishingly rare in the overall astrobiological landscape, it is still worthwhile to inquire whether our specific SETI methodologies are, in one way or another, inconspicuously rooted in peculiarities of this particular reference class of observers. In other words, we need to ask ourselves to

what extent the detectability of other types of observers is a consequence of the systemic properties of their physical environment – as opposed to being product of the contingencies and happenstance of the entire (biological + cultural) history.

Consider the theoretical assumptions of our own SETI projects. Since the early days of the “Founding Fathers” in 1950s and 1960s, most practical activities in the field have relied on radio waves as presumed carrier of extraterrestrial signals. The precepts of Cocconi and Morrison [19] held firm in this regard, and in fact any suggestion of an alternative SETI, theoretical or empirical, has been often downplayed as fantastic or simply ignored. The key resource database is <https://technosearch.seti.org>, maintained by the SETI Institute. That site is an attempt to catalog all published SETI searches since Project Ozma in 1960. It is organized into three different lists: Radio, Optical, and Archival; “optical” list includes wavelengths from γ -rays through the far-infrared, and “archival” list contains searches that have used previously published data to search for technological artefacts. While some early examples are present, in particular theoretical analyses of advanced technology by Dyson and of optical SETI by Townes and Schwartz in early 1960s, it has been only since the turn of the century (partially for technological reasons) that more serious non-radio searches have been performed. And the atmosphere has changed to the effect that in recent years (roughly since 2010) the alternative approaches, such as extragalactic (e.g., 20-22) or Dysonian SETI [23] have received more mainstream acceptance. Of course, more work in history of science is necessary in order to elaborate upon this development; the present manuscript has no such aspirations. Instead, we wish to focus upon one particular aspect in which our conventional technological practices in the SETI field are in tension with the ubiquitous evolutionary contingency.

This issue is by no means too specific or parochial: it touches upon the key topic of *cultural convergence* upon which all SETI projects are based (even if it is too often only tacitly admitted by the research community). Following the original argument of Simpson [24], the great geographer and evolutionist Jared Diamond has argued that particular features of human culture, such as radio, are likely to be contingent within the context of cultural evolution [25]. Radio is just a particularly prominent example of direct interest to SETI, but the reasoning we need to reconsider here applies equally to many other aspects of technological evolution.

In this note, we explicitly do not wish to enter the complex debate about habitability of planets around M-dwarfs and whether they could support simple life only, or both simple and complex life, etc. Instead, we wish to discuss the following related questions: *if* planets around red dwarfs are indeed habitable for complex life and intelligence, should we then stick to the conventional orthodoxy of radio searches in their cases? Are there clear physical reasons to adopt different, more efficient strategies for such, and/or sufficiently different habitable locales? If the answer to the latter question is in the affirmative, then it is of crucial importance to consider what other anthropocentric cultural baggage [26, 27] we have unjustifiably smuggled in while conceiving and planning our SETI programs.

2 CONTINGENT NATURE OF RADIO COMMUNICATION

Why, exactly, should we assume radio communication as typical in a wider astrobiological context? One of the most influential contemporary intellectuals, evolutionary biologist and his-

torian Jared Diamond has argued forcefully against our SETI efforts on the basis of their blithely assumed convergence. He paraphrases this assumption as follows:²

If you expose millions of species for millions of years to similar selective forces, of course you can expect similar solutions to emerge time and time again. We know that convergence is very common among the species on Earth, and, by the same reasoning, convergence should also exist between Earth's species and those elsewhere. Hence, although radio communication has evolved here only once so far, considerations of convergent evolution lead us to expect its evolution on some other planets as well.

Note that Diamond does not only ascribes to the SETI proponents the core idea of continuity of cultural and biological evolution – he does accept it himself in order to show that it is *insufficient* for supporting the SETI position. The essence of his counter-argument rests upon the example of woodpecking. It is an empirical fact that woodpeckers are an extremely well-adapted species, whose complex adaptations enable them to fill a stable ecological niche with significant success. Which further leads him to conclude (p. 162):

Consider what biology might have taught us about the inevitability of radio evolution on Earth. If radio building were like woodpecking, some species might have evolved certain elements of the package or evolved them in inefficient form, although only one species managed to evolve the complete package. For instance, we might have found today that turkeys build radio transmitters but no receivers, while kangaroos build receivers but no transmitters. The fossil record might have shown dozens of now-extinct animals experimenting over the last half billion years with metallurgy and increasingly complex electronic circuits, leading to electric toasters in the Triassic, battery-operated rat traps in the Oligocene and, finally, radios in the Holocene.

A detailed criticism of logical and empirical aspects of Diamond's argument is given in Ćirković [29]. Here we wish to bring attention to another, usually disregarded aspect of this evolutionary argumentation, namely that even if we fully accept the continuity between biological and cultural evolution, as well as high adaptive value of radio communication on Earth, this is still insufficient for the strong convergence conclusion [30]. In particular, there may be wide classes of habitats in which radio communication has much lower adaptive value, or none at all.

We need explicitly *astrobiological* evolution to account for selection pressures at the very high levels of joint (biological + cultural) evolution. In a way, this has been recognized; one of the early SETI pioneers, Michael Papagiannis noticed back in 1984 that the very limits of sustainability might act as a selection pressure, filtering out profligate and wasteful civilizations [31]. This study is one of the very first in which the continuity of biological and cultural evolution was emphasized in its natural, astrobiological context. Obviously, astrophysical distribution of resources dictates the intensity of this kind of selection pressure.

We should expect other abiotic selection pressures, one of them being adequately generalized space weather. The conventional definition of space weather is pragmatic and anthro-

² Ref. 28, p. 158..

pocentric (e.g. The US National Space Weather Strategy and Action Plan 2019³):

Space weather comprises a set of naturally occurring phenomena that have the potential to adversely affect critical functions, assets, and operations in space and on Earth. Extreme space weather events can degrade or damage critical infrastructures, which may result in direct or cascading failures across key services such as electric power, communications, water supply, healthcare, and transportation. The Sun can create space weather events that have the potential to substantially disrupt or damage critical functions, assets, and operations in space and on Earth, including critical infrastructure and technology systems.

Clearly, this statement could and should be generalized to include stars other than the Sun and their habitable and potentially inhabited planets. Space weather generalized in such a way is necessarily part of the abiotic selection pressure acting on the set of technological civilizations in the Galaxy.

It is very well known that space weather influences many aspects of contemporary human civilization on Earth, such as satellites [32], high-latitude electric power grids [33], commercial airplane traffic [34], or human radio communications themselves (e.g., [35]–[37]). Extreme space weather events, like the Carrington event of 1859, present an acknowledged global risk for modern civilization accustomed to electronics and long-range communications [36]. Space weather on and near Earth, however, is *extremely nice and clement* in comparison to other astrophysical locales, and notably in comparison the environment around flaring and magnetically active M-dwarfs. Both persistent and intermittent activity of such stars, coupled with the necessarily small distance of planets within their circumstellar habitable zones, create space weather conditions which are orders of magnitude more extreme than anything that could ever be encountered on and near Earth. Consequent impact on technological systems of our cosmic peers – and targets to be chosen in SETI surveys – should be correspondingly larger and lead to diverging outcomes, when compared with our situation. Taking into account the abundance of M-dwarfs and planets around them, this effect might be dominant overall and seriously jeopardize our conventional SETI strategies.

3 M DWARF FLARES AS SOURCES OF RADIO NOISES

That M-dwarf flares emit substantial electromagnetic noise has been known since the early days of radio astronomy. Direct detection of cool main-sequence stars in the radio domain beyond 10–20 pc is still very difficult, however. Radio emissivity is highest in the very early stages of stellar evolution, near Zero Age Main Sequence (ZAMS), although the ages of M dwarfs are very poorly constrained [38]. Majority of M dwarfs belong to the magnetically active category (160 of 238 in the example of [39]). These dMe stars possess magnetic fields 10–100 times the strength of Solar magnetic field, and their frequent intensive flares are accompanied by coronal mass ejections and formation of complex persistent magnetospheric structures as large as $10 R^*$. If the radius of a typical M dwarf is similar to the radius of Proxima, about 1.07×10^5 km, scales of these magnetic structures are large enough to partially overlap with sizes of

the circumstellar habitable zone. Space weather on worlds located in these habitable zones is necessarily extremely complex, and orders of magnitude more intense and inclement than in the case of Earth.

Observations of Proxima by Davenport et al. [40] show that “normal” flares of energies about 1028 ergs occur on the average 63 times a day, while “superflares” at 1033 ergs or more occur on the average 8 times per year. While flares like these could be major destructive influences on the biospheres of planets around red dwarfs and could possibly cause mass extinction episodes even on Earth, which is 1 AU distant from a quiescent star like the Sun [41], we neglect this more general aspect of flaring here, concentrating on the effects of space weather on presumed technological civilizations. Segura et al. [10] investigate effects of a strong flare of April 12, 1985 on red dwarf AD Leo by simulating the effects from both UV radiation and protons on the atmospheric chemistry of a hypothetical, Earth-like planet located within red dwarf’s habitable zone. Of particular concern is the decrease in ozone column density as a consequence of high-energy photons and protons. The conclusions of these authors are, however, optimistic in the sense that the impact of strong flares on the atmospheric ozone is quite modest and unlikely to seriously damage a hypothetical biosphere. Somewhat different results have been obtained by Howard et al. [42] for the Proxima 2016 superflare, their models indicating rather strong ozone depletion at Proxima b, with atmospheric parameters taken to be Earth’s. In addition, there are other possibly adverse effects, such as desiccation of planetary water [41]. Irrespectively of this controversy, if we suppose that at least some biospheres around M dwarfs can evolve technological civilizations, they would still face space weather incompatible with the extensive use of radio communications familiar from our experience.

Solar flares are known to cause so-called radio fading events at HF (3–30 MHz) range, characterized by decrease in signal amplitude due to increased ionospheric electron density. Such events on Earth can last up to several hours and cause dramatic increase in the noise in HF bands, including the complete loss of signal [35]. These effects are likely to be magnified by at least two orders of magnitude or more for hypothetical inhabitants of planets around M dwarfs. This is strongly dependent upon the unknown planetary magnetic fields, although it must be noted that planets in habitable zones of red dwarfs are likely to be slow rotators – tidally locked or in Mercury-like resonances – with weak magnetic fields [11].

Several recent studies have measured the intensity of radio bursts of M-dwarf stars (e.g. [43]) related to flaring. Many long bursts, of the duration of an hour or several hours are detected with peak flux densities of 10–200 mJy in the frequency interval 1–6 GHz, which is exactly the one of interest for the traditional SETI (since it includes the “water hole” range). Frequency drifts also occur in almost all bursts, on variety of timescales; this would make maintenance of reliable radio communication even more difficult. Similarly, the March 24, 2017, radio flare of Proxima reached peak intensity of 100 mJy, about three orders of magnitude higher than the persistent emission in the quiescent state [44]. To further put it into perspective, this peak intensity is about an order of magnitude greater than the typical source flux at 21cm in the VLA SETI observation of Gray and Marvel [45], and 50–100 times the intensity of typical noise in radio maps at 6.25 GHz.

The Arecibo message was transmitted at a power of 1 MW.

³ <https://www.whitehouse.gov/wp-content/uploads/2019/03/National-Space-Weather-Strategy-and-Action-Plan-2019.pdf>, last accessed September 25, 2019.

Assuming a transmitting bandwidth of 10 Hz this translates to radio flux of 10 μ Jy. With the sensitivity of the upcoming state-of-the-art modern radio telescopes reaching the sub- μ Jy scales, this message would be detected at distances in excess of 10 pc. However, at a Proxima-like distance of ~ 1 pc the signal strength would be of the order of ~ 1 mJy which is some two orders of magnitude smaller than the strength of Proxima Centauri radio flares. The Arecibo message broadcast was less than three minutes in duration, which would make an analogue likely to overlap with periods of high stellar activity. For the detected M dwarfs' radio bursts, Villadsen & Hallinan ([43], Table 3) report peak flux uncertainties ranging from $\sim 1\%$ to $\sim 40\%$. All this puts the traditional SETI attempts, such as the Arecibo message, in the noise region of the typical stellar activity.

These comparisons are, of course, of limited value, since it is highly improbable that – taking into account the local space weather – large installations such as the Arecibo telescope would have been built by a hypothetical Proximan civilization in the first place. It seems only reasonable to assume that such a civilization would tend to use other methods of long-range communication both for internal purposes and for hypothetical interstellar communication. Such methods may be those already conceived by present-day humans (e.g., [46]), like gamma-rays or inscribed matter packages, or hitherto unimagined “wild cards”.

4 DISCUSSION

The idea that radio communication is essentially convergent – that it will emerge independently in the course of (biological + cultural) evolution in many Galactic biospheres – is of key importance for the traditional SETI. Ever since Tesla and Marconi invented radio, via Cocconi and Morrison [19] and the OZMA Project, to the *Breakthrough* Initiatives of today, radio communication has been seen as the most efficient way of transmitting information over long, incl. interstellar distances. The traditional SETI is based on the idea that radio communication is a rule, and that the other ways of communicating like optical lasers, gamma-rays, neutrinos, gravitational waves, or inscribed matter artefacts, if they exist somewhere at all are contingent exceptions, happenstance. Some of the limitations of this approach have been known for quite some time [47]. However, this idea emerged in the context of human history and human technological evolution, predicated upon the relative radio quiescence of our Sun and very clement space weather for most of the time since *homo sapiens* developed technological civilization. These physical circumstances should not be taken for granted at all – and especially should not be taken for granted now that we know much about the spatiotemporal distribution of habitable planets in the Galaxy. In the case of M dwarfs, we may have, ironically, a kind of see-saw effect: while strong magnetic fields may indeed help habitability of planets around such stars, they might simultaneously suppress the kind of technology, namely radio, which could make the emerging technological civilizations there detectable.

Copernican reasoning would suggest that since the one example of a known technological civilization orbits a G-type star, we should – lacking deeper empirical knowledge – expect that others will as well. If M-dwarfs dominate in the set of Galactic habitable planets and if habitable planets around M-dwarfs dominate in the subset of habitable planets evolving intelligent life, this assumption used in the traditional SETI may be unfounded, as described above. A straightforward consequence would be the corresponding methodological shift. Radio com-

munications in the vicinity of M-dwarfs would be much less efficient, less reliable, and more expensive than what has been experienced in human history, our being located around a G-type star. Thus, technological civilizations arising around M-dwarfs would be pressured into developing other mentioned ways of first planetary and later interplanetary and interstellar communication.⁴ In other words, the pathway of technological evolution of such intelligent communities will likely diverge from our pathway in several respects. One of these is exactly the key for detection and/or communication over interstellar distances. Hence, our SETI efforts should be modified accordingly. If our present view is correct, we can predict the lack of any SETI-interesting radio sources from the vicinity of red dwarfs, even if it possesses planets in its circumstellar habitable zone [48].

There is a wider and more important philosophical and methodological consideration behind this and similar practical issues: the emancipation from anthropocentrism and fully endorsing the diversity of habitats in the overall astrobiological landscape [27]. It could be regarded as analogous to the process of Bayesian learning: in the beginning we knew very little about physical conditions of other Galactic habitats and as we learn more and more, we have to modify and update our optimal strategies. There has been strong recalcitrance to such process in the circles of the traditional SETI. One unfortunate side effect of this recalcitrance is exactly that it strengthens the hand of those radical sceptics who would gut the entire SETI enterprise, as is the case with Jared Diamond. Furthermore, it is important to notice that there are also distinguished astrobiologists arguing for at best scepticism regarding SETI, at least in part on the basis of evolutionary contingency [49, 50].

Diamond criticized the *whole* of SETI on this basis; while it can be shown that his general argument fails and that evolutionary convergence does indeed leave the doors open for cautious optimism in regard to SETI [25, 29], there are *particular* SETI issues where Diamondian scepticism is more justified. The issue of hypothetical technological civilizations evolving around M dwarfs in light of the traditional radio SETI is one such example. In light of the above it is unlikely that radio will be a convergent feature of the cultural evolution of such civilizations – if they arise in the first place, of course. Even if they subsequently develop satisfactory shielding from flares [51] or colonize different planetary systems with calmer space weather [52], it is quite likely that cultural quirks will persist, be sufficiently entrenched, and suppress, *ceteris paribus*, relative frequency of the radio usage, as compared to the other methods of long-range communication (such as those listed in [46]). Therefore, we need to do the same while targeting – extremely numerous – planetary systems of M-dwarfs in our SETI surveys. In the same time, we need more systematic analysis of our anthropocentric quirks and peculiarities in order to correct for multiple biases of our historically contingent culture and formulate truly objective SETI programs. Hence, the current issue represents an excellent example of the urgent need to overcome the disciplinary barriers and to formulate true multidisciplinary research programs, in which our insights in astrophysics, astrobiology, and SETI studies could be fruitfully joined with those of the studies of culture, history of science and technologies, and humanities in general. An approach along these lines is certainly the Dysonian SETI [20-23].

⁴ In the specific case of M-dwarfs, UV and soft X-ray communications would be intermittently suppressed as well by their XUV flaring and coronal ejections [10].

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ON A SPECTRAL PATTERN OF THE VON NEUMANN PROBES

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In this paper we have extended our previous work and considered the spectral characteristics of interstellar non-relativistic von Neumann probes launched by Kardashev Type-II and Type-III civilizations. It has been shown that by means of the proton capture, required for replication, strong bremsstrahlung emission will be generated. We have found that for both types of civilizations the probes might be visible mainly in the infrared spectral band, but as it has been found the probes might be visible in the ultraviolet as well. For both cases it was shown that differential power has dips for equally spaced frequencies, which might be a significant fingerprint to identify such exotic interstellar objects.

Keywords: von Neumann Probes, SETI, Extraterrestrial life-detection

1 INTRODUCTION

In the previous paper (henceforth paper-I) we have considered self-replicating von Neumann extraterrestrial probes [1]. In this work we considered Type-II civilization self-replicating extraterrestrial robots and estimated their length-scales. We found that for making a process of colonization of space very efficient, the probes must be of micron size. Then, in a molecular cloud the typical timescale of replication might be several years, which might lead to potentially detectable very intense radiation. In Paper-I we estimated orders of magnitude of radiation frequency, bolometric luminosity and its increment, but did not study the spectral characteristics of emission, the study of which is a purpose of the present work. The idea of self-reproducing probes has been proposed in the last century by von Neumann [2]. In particular, he studied the possibility of machines with artificial intelligence capable of self-reproduction and the problem has been examined in the context of information theory and corresponding thermodynamics. This idea also has been revisited in the context of the search for extraterrestrial intelligence (SETI) [3]. After the discovery of 'Oumuamua's unusual behaviour [4], the interest to the study of extraterrestrial probes has been revived, despite the natural explanation of the aforementioned peculiarity [5].

In general, the study of techno-signatures of advanced extraterrestrial civilizations has been actively discussed since a brilliant idea of Dyson [6], who proposed to search for Type-II [7] civilizations by searching for infrared spheres (Dyson spheres – DS) built around stars. It is worth noting that according to Kardashev's classification Type-I is a technological civilization which uses the total energy coming from the host Solar-type star to the Earth-like planet, Type-II is an advanced alien society harnessing the total energy emitted by the star and Type-III civilization is capable to use the total energy of the host galaxy. The interest to techno-signatures has revived after the discovery of a strange behaviour of the Tabby's Star's (KIC8462852 in the Kepler Input Catalog) flux, characterised by unusual high dips [8]. The problem is so complex that Dysonian SETI should be revisited and widened [9]. Interesting attempts have been

presented in a series of papers [10-17].

In this context our previous work (Paper-I) where we have studied the von Neumann interstellar Type-II probes,¹ merits special interest. The main aim of the paper was a) to show high efficiency of small sized probes in colonising the space and b) estimate very general characteristics of the emission pattern. In the paper-I we have examined the probes with three possible velocities: $0.01c$; $0.02c$; $0.1c$ (c is the speed of light) and it was shown that number of the probes increases drastically by the factor of 1032 during 650yrs ($v = 0.01c$), 320yrs ($v = 0.02c$), 60yrs ($v = 0.1c$). Which are quite realistic values because they are small compared to a timescale (3000yrs) required for Type-I civilization to reach the level of Type-II [6]. We have found that the probes might be seen from radio to infrared spectral band and estimated the luminosity increment time-scales which lie in the interval (1-10)yrs and the corresponding achieved luminosities might be enormous, at least of the order of 10^{16-20} erg/s.

The aim of the present paper is certain extension of paper-I. In particular, we are going to study the spectral characteristics of the probes studying energy emitted by the unit of time per unit of frequency for Type-II and Type-III extraterrestrial probes.

The paper is organized in the following way: in Sec. 2, we consider the general tools and methods, applying them to Type-II and Type-III civilizations and obtain corresponding results and in Sec. 3 we outline the summary of the results.

2 MAIN CONSIDERATIONS

As we have already shown in the previous work, the mass rate for a spherical probe is given by [1]:

$$\frac{dM}{dt} = \pi \beta r^2 m_0 n c \quad (1)$$

¹ In Paper-I a) Eq. (2) the probe's size and density should be $0.01 \mu\text{m}$ and 1 cm^{-3} and in b) the optimal size should be 10^{-6} cm instead of $7 \times 10^{-6} \text{ cm}$.

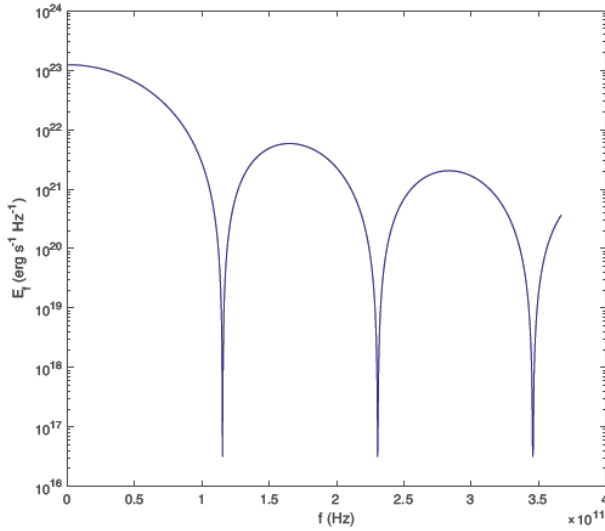


Fig.1 The behaviour of E_f versus frequency. The set of parameters is: $\beta = 0.01$, $N_0 = 100$, $\zeta = 0.1$, $m_0 = m_p$ (m_p is the proton mass), $\rho = 0.4 \text{ g cm}^{-3}$, $n = 10^4 \text{ cm}^{-3}$, $D = 2 \text{ pc}$.

where r is the radius of the probe, $\beta = v/c$ is a dimensionless velocity, c represents the speed of light and m_0 is the mass of a molecule the probes encounter and n is the number density of particles in a cloud. By taking into account an expression for the mass of the spherical probe, $M = 4\pi\zeta r^3 \rho / 3$, the timescale of replication writes as:

$$\tau = \frac{M}{dM/dt} = \frac{4\zeta}{\beta} \times \frac{\rho}{m_0 n} \times \frac{r}{c} \simeq 3.4 \times \frac{\xi}{0.1} \times \frac{0.01}{\beta} \times \frac{\rho}{0.4 \text{ g cm}^{-3}} \times \frac{10^4 \text{ cm}^{-3}}{n} \times \frac{r}{0.1 \text{ mm}} \text{ yr s} \quad (2)$$

where ξ denotes the fraction of the total volume filled with the material the probe is made of, and the corresponding density is normalised by the Graphene density (up to now the strongest material). As it is clear from the above expression time required for replication of a single probe is of the order of several years. This in turn means that in a nebula with a length-scale 2pc the multiplication factor, $2^{t/\tau}$, becomes of the order 10^{48} , which indicates high efficiency of the process. By assuming the initial number of robots 100, one can straightforwardly show that an average distance between probes is of the order of 1m. The time-scale has been estimated for the typical parameters of HII interstellar atomic hydrogen cloud [18].

In Paper-1 we have discussed that the probes when collecting the cloud atoms or molecules will inevitably lead to observable events. In particular, it is easy to show that a single probe capturing protons will accelerate them with the acceleration $a \sim v^2/(2\kappa r)$, where κ is a dimensionless parameter characterizing an acceleration distance). This process in turn will lead to the Larmor emission and as a result, by means of the multiple events of proton capture, the bolometric luminosity corresponding to a single probe is given by [1]:

$$L_p \simeq \frac{\pi}{3\kappa} n r c e^2 \beta^4 \quad (3)$$

leading to the total luminosity of the ensemble of self-replicators:

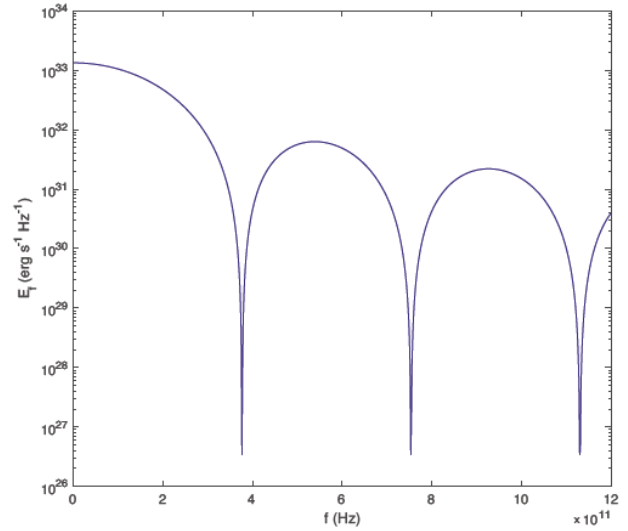


Fig.2 The dependence of E_f on frequency. The set of parameters is the same as in the previous graph except $n = 1 \text{ cm}^{-3}$ and $D = 50000 \text{ pc}$.

where N_0 indicates the initial number of robots. Throughout the paper we use $k = 0.1$)

$$L_{tot} \simeq \frac{\pi}{3\kappa} n r c e^2 \beta^4 N_0 \times 2^{t/\tau} \quad (4)$$

As it has been shown in [1], for a given medium there is a certain relation between the probe size and the length-scale of a space, D , the ensemble is supposed to occupy reaching some critical (maximum) luminosity, L_{cr}

$$\frac{3 \ln 2}{4\zeta} \times \frac{m_0 n}{\rho} \times \frac{D}{r} \simeq \ln \left(\frac{L_{cr}}{N_0 L_0(r)} \right) \quad (5)$$

Unlike the previous study, in this paper we consider both types of advanced civilizations: Type-II, harnessing the total energy of its host star and Type-III utilizing the energy of a galaxy [6]. For Type-II probes the critical luminosity is of the order of the Solar luminosity, $L_{\odot} \approx 3.8 \times 10^{33} \text{ ergs s}^{-1}$, whereas for Type-III the critical value should be of the order of the bolometric luminosity of the galaxy. As an example we examine the Milky Way galaxy $L_{\alpha} \approx 3.6 \times 10^{10} L_{\odot}$ [18]. The aforementioned equation should be solved numerically and in the former case, for a spherical cloud with a length-scale $D \approx 2 \text{ pc}$ one obtains the probe size of the order of 0.025cm and for the latter, by taking into account the diameter of the Milky Way galaxy $D \approx 50000 \text{ pc}$ one has $1.28 \times 10^{-5} \text{ cm}$. The calculations have been performed for $\beta = 0.01$.

In the previous study we have considered only a general emission pattern, without going into special characteristics. On the other hand, identification of the probes requires a detailed study of the emission process. Therefore, the major aim of the paper is to examine the spectral energy distribution of self-replicating von Neumann probes. For this purpose we consider radiated energy per unit of frequency [19]

$$\frac{dW}{d\omega} = \frac{8\pi\omega^4}{3c^3} \times |\hat{d}(\omega)|^2 \quad (6)$$

where ω is the cyclic frequency of emission and

$$\hat{d}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} d(t) e^{i\omega t} dt \quad (7)$$

is the Fourier component of the dipole moment. By considering the Fourier transform of its second time derivative, one obtains [19]:

$$-\omega^2 \hat{d}(\omega) = \frac{e}{2\pi} \int_{-\infty}^{+\infty} a(t) e^{i\omega t} dt \quad (8)$$

where e is the proton's charge and $a(t)$ is the corresponding acceleration when encountering the probes. If one approximates it as a constant value, a , during an interaction time $\tau_0 \approx 2\kappa r/v$, then it is straightforward to show:

$$\hat{d}(\omega) = \frac{ea}{\pi\omega^3} \left| \sin\left(\frac{\omega\tau_0}{2}\right) \right| \quad (9)$$

reducing Eq. (6) to the following form:

$$\frac{dW}{df} = \frac{4\pi e^2 \beta^2}{3c} \times \left(\frac{f_0}{f}\right)^2 \sin^2\left(\frac{f}{f_0}\right) \quad (10)$$

where $f_0 = \beta c / (2\pi\kappa r)$ and we have taken into account $\omega = 2\pi f$. The derived formula characterises a single event of a proton capture. To obtain the total emission per unit time and unit frequency interval (spectral power), $E_f \equiv dW/(dt df)$, we note that the incident proton flux is $n_p c \beta$, then one can write:

$$\frac{dW}{dt df} = n_p N(t) \frac{4\pi e^2 r^2 \beta^3}{3} \times \left(\frac{f_0}{f}\right)^2 \sin^2\left(\frac{f}{f_0}\right) \quad (11)$$

where

$$N(t) = N_0 \times e^{t/\tau} \quad (12)$$

is the total number of probes. As a next step, we are going to apply the obtained expressions to Type-II and Type-III civilizations.

2.1 Type-II interstellar probes

In this subsection we examine the von Neumann probes belonging to Type-II societies. For this purpose we consider a spherical nebula with a radius of the order of 1 pc, then, as we have already shown the optimal length-scale of the robot should be of the order of 6.63×10^{-6} cm leading to the corresponding characteristic emission frequency²

$$f_0 \simeq \frac{\beta c}{2\pi r \kappa} \simeq 3.7 \times 10^{10} \times \frac{\beta}{0.01} \text{ Hz} \quad (13)$$

In Fig. 1 we plot the dependence of E_f on frequency. The set of parameters is: $\beta = 0.01$, $N_0 = 100$, $\zeta = 0.1$, $m_0 = m_p$ (m_p is the proton mass), $n = 10^4 \text{ cm}^{-3}$, $D = 2 \text{ pc}$. As it is clear from the figure, the spectral power of von Neumann probes has a specific fingerprint: at certain frequencies E_f diminishes. From Eq. (11) one can straightforwardly show that the spectral power becomes zero for the following discrete set of equally spaced frequencies $f_k = f_0 \pi k$ for $k = 1; 2; \dots$. The presented spectral behaviour is drastically different from black body spectrum as well as from the thermal bremsstrahlung, which can be a very important factor in identifying the von Neumann interstellar probes.

² The velocities of the probes are not relativistic and therefore, the Doppler shift does not affect the result.

Another interesting feature is that if one considers a different value of β , the corresponding length-scale of the probe will be different, but the overall spectral feature will be the same - in this sense the given spectrum is unique. The initial number of probes 100, very rapidly multiplies and approximately in 650 yrs the total number will be of the order of 10^{50} colonising the whole nebula. One should also note that if one maintains an annual growth rate of 1% in industry, then 3000 yrs is quite enough to reach such an advanced technological level, which means that the assumption of existence of such alien societies is quite reasonable [6].

2.2 Type-III interstellar probes

As it has been classified by Kardashev [7] advanced civilizations consuming almost the whole power of their host galaxy ($\sim 4 \times 10^{44} \text{ ergs s}^{-1}$) is the so-called Type-III society. Our own civilization consumes approximately $4 \times 10^{19} \text{ ergs s}^{-1}$, which means that if an average 1% of annual growth is maintained our society will achieve Type-III in 6000 years, which like the previous case, is a negligible value on the galactic timescale.

For making estimates, we consider the parameters of the Milky Way, having the diameter 50,000 pc and the total luminosity $3.6 \times 10^{10} L_\odot$. Then, by taking into account the number density of interstellar protons 1 cm^{-3} for the optimal size of the probe one obtains 0.025 cm (see Eq. (5)), which means that the frequency describing the spectral energy distribution is of the order of $1.2 \times 10^{11} \text{ Hz}$ - infrared spectrum.

In Fig. 2 we show the behaviour of E_f versus f . The set of parameters is the same as for Type-II civilizations except $n = 1 \text{ cm}^{-3}$ and $D = 50,000 \text{ pc}$. Like the previous case, one can see that emission spectra of Type-III probes vanish for a discrete set of frequencies $f_k = f_0 \pi k$ for $k = 1; 2; \dots$ with $f_0 = 1.9 \times 10^{10} \text{ Hz}$. For the considered value of velocity, the timescale of colonising the whole galaxy is of the order of $T \approx D/(2\beta c) \approx 16 \text{ Myr}$, which is by three orders of magnitude less than the galactic age, 10 Gyr. Therefore, colonization in the context of timescales might be quite reasonable. From Eq. (12) one can straightforwardly show that after the mentioned time, the multiplication factor will be of the order of 10^{58} leading to the total luminosity of the order of the galactic luminosity. Peculiarity of the emission spectra, characterised by equally spaced dips and the overall dependence on frequency, which is different from all other spectral behaviours, might be a good sign to identify the Type-III interstellar von Neumann probes.

Recently new prospects appeared thanks to the 500 m Aperture Spherical Radio Telescope (FAST) - a single-dish radio telescope that is going to work in the SETI projects as well [20]. On the other hand, radio emission of von Neumann probes is efficient. In particular, for Type-II probes the total power emitted in the Hydrogen line (1.42 GHz) will be of the order of $10^{32} \text{ ergs s}^{-1}$.

3 CONCLUSION

We have studied the spectral characteristics of Type-II and Type-III von Neumann self-reproducing interstellar probes. For this purpose we have considered emission generated by proton capture and examined the corresponding mechanism of bremsstrahlung.

Considering Type-II robots it has been shown that to colonise the spherical nebula with radius of the order of 1 pc, the

optimal length-scale of the probe should be 0.013cm, leading to emission from radio to infrared. It has been found that the differential emission power has equally spaced dips in frequency. The same behaviour has been found for Type-III interstellar probes as well (also potentially observable from radio to infrared), which might be a significant indicator to identify these exotic robots.

Generally speaking, we have analyzed the emission pattern for certain typical parameters. Consequently for different values the emission spectra will be different, but what is very im-

portant, a general fingerprint - the particular behaviour, with periodic dips - is maintained and in this sense the mentioned results are unique. Therefore, if one finds the similar dependence of spectral power on frequency, this might be a significant result indicating the existence of von Neumann interstellar probes.

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REWORKING THE SETI PARADOX:

METI's Place on the Continuum of Astrobiological Signaling

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The Search for Extraterrestrial Intelligence (SETI) has heretofore been a largely passive exercise, reliant on the pursuit of technosignatures. Still, there are those that advocate a more active approach. Messaging Extraterrestrial Intelligence (METI) has had a controversial history within the larger SETI project; it is claimed that the risks involved outweigh any potential benefits. These arguments are ultimately not compelling, result in absurd policy recommendations, and rest on a faulty appreciation of the nature of technosignatures, whose detectability implies intent to signal. Present technology is advancing quickly such that we will soon have great observational reach, to the point of reliably detecting such technosignatures and biosignatures: a capability that can be matched or exceeded elsewhere. To escape the SETI Paradox properly defined, at least one technological civilization must choose not to suppress its own continuum of astrobiological signals, of which METI is merely the most effective endmember. Passive SETI's low likelihood of success in the short-term is a serious obstacle to sustainable funding, alongside a 'giggle factor' enhanced by a pernicious fear of contact. The scientific community must integrate an active approach to better ensure both the continuity and eventual success of the SETI project.

Keywords: METI, SETI, Astrobiology, Technosignatures, Biosignatures

1 INTRODUCTION

The plurality of worlds is an ancient dream: thanks to modern astronomy, we understand it at last to be reality. So long as we dreamt of those worlds, we often supposed them inhabited, usually by beings quite like us. The Search for Extraterrestrial Intelligence (SETI) has spent the last six decades scanning the skies for signs of such extraterrestrial technologists (ETs). Despite plausible estimates that project dozens of other technologically advanced civilizations to exist within the galaxy [1], to date none have been found. This is the Great Silence: a puzzle that has since its inception captivated the astrobiological community, and many others besides. Where are the aliens?

There are two established ways to answer this question. One is to detect a biosignature: some 'object, substance and/or pattern whose origin specifically requires a biological agent' [2]. On worlds presently unreachable by in-situ analysis and remote sensing by spacecraft, these phenomena will be rendered as one or more spectral features that indicate atmospheric gases or surficial reflection, best considered in the context of their planetary and stellar environments [3,4]. Some traditional biosignatures include O₂, O₃, nitrogen oxides (NO_x), complex sulfur gases, photosynthetic pigments, redox disequilibria, or seasonal oscillations of the same [3,4].

SETI sets itself apart from the larger astrobiology project as the hunt for technosignatures: detectable features indicative of an environment modified by technology [5]. Common biosignatures can be created by abiotic processes, but technosignatures provide increased confidence in the detection of extraterrestrial life [3]. Many kinds of technosignatures have been

proposed, and different SETI disciplines have evolved to find them [6]. Communications SETI aims to find communications leakage or directed messaging from ETs across the electromagnetic spectrum. Artifact SETI searches for ET's environmental footprint, manifested by such things as artificial structures, atmospheric pollution, waste heat, or space probes a-la-Voyager. Inexplicable anomalies in nature can also point to the presence of ETs, though with less certainty. Traditionally, most time and effort has been dedicated to radio SETI, as immortalized in Carl Sagan's *Contact*.

The object of such 'passive' SETI efforts is to search for technosignatures across the electromagnetic spectrum. Still, there are those within the community that advocate a more active approach. METI (Messaging Extraterrestrial Intelligence), or Active SETI, involves the intentional sending of messages or recoverable probes, in the hopes of eliciting a reply. To date, 16 distinct messages have been transmitted to 26 different targets [7], plus the Voyager Golden Records and Pioneer plaques. Taken liberally, the five spacecraft humanity has sent on interstellar trajectories themselves count as METI. Despite this storied history, METI's position within the larger SETI project has long been controversial. It is often seen, quite literally, as 'searching for trouble' [8]. The argument over METI's legitimacy and effectiveness has raged since the Arecibo Message was sent in 1974 and continues to this day.

1.1 The METI Debate

METI proponents, hereafter *metiists*, have historically proffered many arguments in favor of their position. Chief among them is advocacy for a diversity of strategy in the SETI project,

especially after so many years of non-detection. Doug Vakoch, head of METI International, maintains that 'through METI we can empirically test the hypothesis that transmitting an intentional signal will elicit a reply' and that objections to METI suffer from various psychological biases [9]. He and Shostak claim that any ET with somewhat greater technical capacity could detect humankind's radio communications leakage [9,10], and Zaitsev takes this a step further by declaring this makes it impossible to hide from more advanced civilizations [11]. Additionally, powerful radar soundings of asteroid and planetary surfaces have proved integral to the study of their morphology and dynamics, and treating such transmissions as dangerous could discourage dedicated systems from being built, and reduce humankind's ability to precisely chart the ephemerides of Potentially Hazardous Objects [12]. More prosaically, Cold-War era over-the-horizon radars were powerful and even diurnal radio sources that could be detected by ETs [13].

In short, metiists typically maintain that our communicative, technological society has betrayed our presence to ETs, whatever their disposition; though Vakoch maintains that SETI itself relies on altruistic messaging from the other side [9]. Metiists tend to hold that ETs are likely neutral or benign, and paint rosy pictures of the outcomes of contact. They offer humanistic reasons to engage in METI too – in distilling what is best about humankind, singular low-impact efforts like the Arecibo message and Voyager Golden Records stand far more robustly as messages to *humans* about SETI than as practical attempts to contact aliens. Transmissions also act as time capsules to provide information about civilizations that may no longer exist, and consequently have archaeological and cultural value [14]. Zaitsev provides perhaps the most heartfelt arguments, looking to history to say that *not* reaching out to other civilizations could lead to the human species' extinction through apathy and isolationism. Most poetically, he frames METI as an answer to the Great Silence [9].

METI opponents, hereafter *passivists*, have developed answers to these arguments and claims of their own. They maintain that passive SETI's lack of success so far is no indication of its capacity to accomplish its goals and that tempting fate by transmitting constitutes 'reckless endangerment of all mankind' [15,16]. Whether it is asserted that we cannot know the motives of ETs [8], and thus ought to beware, or that we can, and they must be accordingly malign; whether it is imagined technologists would travel to Earth to harvest our resources [17], enslave humanity [18] or, more insidiously, have our world destroyed remotely with relativistic or Drexlerian weapons [15], the spectrum of possibility is deemed too great to hazard.

METI advocates stand accused of 'following a naïve faith' that ETs are altruistic or godlike, maintaining breathlessly that the aliens are waiting for us to call, eight arms outstretched in welcome to the Galactic Club [15]. Indeed, some metiists are partisans of the Zoo hypothesis, and optimistic to a fault. Without concrete plans to receive a return message, metiists are said to have no methodology nor sense of empiricism. Indeed, they are hardly scientists at all, more comparable, as passivist-extraordinaire John Gertz acidly puts it, to 'someone who cultures and releases anthrax' [16].

Evolutionary psychologists have attempted to condemn METI as announcing Earth's myriad resources to the cosmos while leaving it 'lightly guarded by a gullible young species' [17]. Similarly, luminaries like Stephen Hawking have compared METI to inviting European colonizers onto First Nations

soil; he maintains that contact had better wait until humans are further developed as a species, both technologically and ethically [19]. The risks of METI today, it is plausibly argued, outweigh the benefits – humankind should instead listen passively for decades, centuries even, before attempting to initiate interstellar contact. Gertz also calls on governmental bodies to make an injunction against METI and prohibit intentional signaling to extrasolar targets at power greater than a terrestrial television broadcast [16].

That specification is considered important, because passivists maintain that humanity's communications leakage cannot be detected by ETs [20]. More to the point, they say METI will not be detected, or if it were, it will not be decoded [13]. Even the 'best case scenarios' (e.g. beams of microwaves used for power transmission) would appear to ETs only as transient events. Moreover, passivists maintain that Earth's detectability window is closing; communications will soon take place through cables, or over directed satellite links [8,15]. Why run the risk when we have yet to show our hand?

Passivists claim too that funding is in the bag and that passive SETI's progress is due to accelerate. The Breakthrough Listen program recently brought in \$100 million over 10 years from magnate Yuri Milner, and passivists duly expect that public funding will follow [8]. Most interestingly, some maintain that the search is nearly over, and ET artifacts could already be in the Solar System, waiting to be discovered [15]; only time will tell.

2 DISCUSSION

It is certainly true, as admirably illustrated by passivists, that many pro-METI arguments fall flat. There is no guarantee that ETs will pick up our communications leakage by itself, or understand its significance, or be able to understand it. The zoo hypothesis is contrived; SETI has indeed just begun its search, and at any rate does not rely exclusively on directed, altruistic messaging. However, little else in the passivist arsenal bears scrutiny, and this debate has been limited almost exclusively to 'orthodox' radio-SETI [6]. As such, passivists neatly skirt the crux of the issue: they fail to see METI's scientific potential and humans as both participants in and objects of the Search for Extraterrestrial Intelligence. Even so, it is still worthwhile to answer detractors' points specifically before moving on to the larger picture.

2.1 Challenges to Passivist Arguments

Trivially, both EM leakage and METI *can* be detected by ETs with sufficiently powerful telescopes; pointing such fantastic instruments in the right direction is a separate if soluble problem, as will be shown later. Moreover, even if transmissions cannot be interpreted, they can provide evidence of a technological civilization in the vicinity of Earth [14], which may be enough to elicit a reply (or, taking passivists at their word, hostilities). Assuming targets to be incapable of decoding transmissions is liable to underestimate the tenacity of advanced species. It is true that metiists are often guilty of using numinous language to describe such ETs; Zaitsev refers to 'highly developed civilizations' as 'something supernatural and mysterious' [11]. This, however, is Clarkean aphorism, not a religious profession – indeed, Gertz makes the same point about magiclike extraterrestrial technology *ad nauseam* [16]. If all that is left to the charge of 'faith' is optimism, then so be it: some humans are condemned to be sanguine.

This does not entail, however, that metiists assume anything about ET's behavior. Indeed, passivists cannot seem to agree on whether *they* can 'know the mind of extraterrestrials' and predict the outcome of contact, the source of the characteristic risk they perceive. Neutral outcomes to contact are just as possible as positive or negative ones [21], entailing that METI will still be useful in all cases save one where we stumble on a 'hostile super-civilization' [18].

Positing that the response of an extraterrestrial intelligence to contact would be malign or predatory relies on assumptions that *cannot be substantiated until contact occurs* [22]. Such projections make themselves predicate on one's priors, and on analogies to human culture [23]. Tempting though it may be to predict alien behavior by looking to human evolution and history, it seems dubious to extrapolate too much from a sample size of one; it is impossible to know whether (aggressive) human behavior is characteristic of intelligent life, though serious attempts have been made to suggest that this is the case [17]. Granted, there is no reason to positively expect a *Star Trek*-style United Federation of Planets either; this is the stuff of science fiction, as are hysterical fears of alien invasion. Indeed, Gertz refers to his own cautionary hypotheticals as 'outlandish' [16], and for good reason. Any disinterested intelligence capable of travelling to Earth and vaporizing our oceans accordingly has the power to fix its own large-scale problems locally, with less effort – and that is provided that our existence is immaterial to it, which may not be the case. Life, or intelligence at any rate, may have value to ETs, or not. There *is* a persuasive element to the axiom that civilizations harmonious enough to last for eons do not, by definition, blow themselves up within the characteristic time frame, but again that is absolutely no guarantee of anything.

More concretely, the incentive for hostility between widely spaced ETs is misaligned. It may be possible to estimate an ET's scientific capabilities in relation to one's own, and perhaps their rate of technological progress and aptitude for aggression, but over vast, interstellar distances the margins of error in these calculations could range many orders of magnitude, a fact as true for remote weapons as crewed visitations. What if ETs, a thousand light years distant, were to receive one of our messages? Humanity could be gone by then, annihilated in a thermonuclear exchange – or, it could be busy settling the nearest twenty systems, playing with Death Stars and laser swords. Granted, there may be unknown methods to escape this time delay, to travel here instantly or know of humankind's state of affairs in real time – but then, who is pretending aliens are gods?

There is a kernel of truth to passivists' claim that METI efforts have been unscientific; however, these are problems of particulars and not fundamental to the METI framework. Certain past transmissions are better thought of as publicity stunts than serious attempts to contact ETs [7]. Additionally, Vakoch's formulation of METI's scientific potential is true but hopelessly narrow and ought be broadened as the following: *METI tests for ETs by actively inducing the data that orthodox SETI waits passively to receive, increasing sampling efficiency and accelerating data acquisition.* It is by design a different approach to the same problem (seeking to find ETs) and deserves its place within the larger, interdisciplinary SETI project [6]. While passivists maintain that astronomy is purely an observatory science and active approaches to it are incoherent, such a view ignores previous interdisciplinary efforts that did exactly that: e.g. the collision of the Deep Impact mission's impactor with Comet 9P/Tempel, which was observed both by the spacecraft bus and

a number of other space-based and Earth-based telescopes.

Again, to passivists' credit, metiists have also not yet articulated a coherent plan to receive return messages; however, this is not entirely their fault. Passivists have determinedly thwarted attempts by metiists to obtain time on large, powerful radio telescopes and without that foot in the organizational door, planning for return messages has been made difficult. Moreover, much like the hostility argument, considering metiists' lack of return plan important fails to appreciate the time delay inherent in sending and receiving messages. While most METI and passive SETI efforts have been focused on nearby stars (scientists like to have questions answered within their lifetimes), many of the most interesting targets of astrobiological scrutiny are hundreds if not thousands of light-years away. Decades or more of time in the interim allows for construction of new astronomical infrastructure (some of which is underway now) and the plan to receive amounts itself to passive SETI. Critically, searching for return messages operates over a small area of sky and a restricted time interval; as such, arguing that we will miss such directed messages reduces to arguing that we will reliably miss unplanned-for transients (at any time and from any direction in the sky) otherwise interesting to orthodox SETI. METI is, in effect, working to speed up the process of contact, to settle the longstanding empirical question posed by the Great Silence once and for all.

Hawking sees this acceleration as a detriment, maintaining humanity needs time to develop the necessary ethics and advanced technology to smoothly engage with extraterrestrials. This is, however, a line of argument just as dangerous to the larger SETI project as to METI. Following his logic and thus supposing humankind were 'not ready' for contact, our own SETI programs would be pointless in the short-term: should we find anything, it would seem at present we are civilizationally incapable of dealing with it. This is an absurd conclusion to draw, as it is not obvious what the effects of discovery would be on the human psyche [24].

Hawking's position voids the push to discard METI on the grounds that SETI will succeed in the near future. This often relies on the assertion that ET probes are here in the Solar System; much though one would like to live in the world of *2001: A Space Odyssey*, we cannot work on the assumption that we do, or that ET exists at all [25]. In that case, why not do what we can to increase the likelihood of discovery?

Similarly, the assertion that Earth's EM detectability window is closing relies on uncertain projections of the future, not just of technology but of its placement within the Solar System. One can imagine scenarios where high-gain, high-power interplanetary communications may be necessary; targets will often be smaller than the cross-section formed by laser or radio beams. Even granting the passivists' hypothesis, the assertion that Earth will soon be undetectable *is not and cannot be true* in the broadest sense.

2.2 Earth as a Planet: Astrobiology and the Copernican Principle

In proposing to regulate Earth's display to the cosmos, passivists consider only orthodox radio technosignatures – yet human activity leaves a planetary-scale, characteristic environmental footprint amenable to an Artifact SETI approach. Atmospheric contamination by artificial pollutants such as chlorofluorocarbons (CFCs) [26], industry-relevant particulates like heavy metals, and geologically rapid changes in trace but significant

gas concentrations (CFCs, CO₂, NO_x, CH₄, O₃) can provide potential technosignatures. Industry has integrated itself with global biogeochemical cycling and that is only projected to intensify as time goes on [27]. As we brace to counter and contend with the effects of climate change, it is worthwhile to note that Earth is in 'hybridized' thermodynamic disequilibrium, a state also considered a potential technosignature [28], though at present the contribution of direct waste heat from human civilization is small. City lights illuminating Earth's nightside, with their diurnal variance and artificial spectral signature, could also be detected by telescopes relying on well-understood technology [10]. It is easy to forget that to any putative aliens, *humans* are ETs too, and thus in considering Earth's signaling potential *all* technosignatures need to be accounted for – not merely the ones that are convenient.

Passive SETI relies on the assumption that some other civilization, having confronted the cosmic emptiness, must have already decided that being detectable to others was worth the risk it entailed; that is, that the detectability of technosignatures *conveys the implicit intent to signal*. At present, humankind is behaving as though detectability were not a problem, engaging neither in an active messaging campaign nor in serious repression of communications leakage or artifact technosignatures. This neutral approach illustrates how concerns about hostile ETs are not held seriously and constitutes unplanned signaling.

Less obviously, biosignatures are part of this conundrum, as they too are by definition detectable. Additionally, they serve as grounds for a targeted, follow-up search for technosignatures if identified. From this, a continuum of astrobiological signaling can be established, ranging from unintentional biosignatures, to passively broadcast technosignatures and onward to active messaging. METI thus stands as an extreme, directed, active technosignature, the difference between it and other astrobiological signaling being one of degree, not kind.

Spectral technosignatures and even biosignatures are on the edge of humankind's detection capabilities now; soon we will have great observational reach to the point of reliably identifying these biogenic phenomena at great distances. The long-delayed JWST will dependably identify atmospheric technosignatures on nearby planets after only a day or so of integration time [26]. The upcoming Nancy Grace Roman Space Telescope (formerly WFIRST, the Wide-Field InfraRed Survey Telescope) and Vera C. Rubin Observatory (formerly LSST, the Large Synoptic Survey Telescope) are both dedicated in part to the discovery of exoplanets [29,30]. Global projects such as the Square Kilometer Array will greatly enhance our radio astronomy capabilities, and LUVOIR (the Large UV/Optical/IR Surveyor) will launch with the intention to directly image and spectrally characterize the atmospheres of exoplanets [31,32]. In the last decade, the notional cost of a kilogram to orbit has dropped by an order of magnitude and may soon fall another thanks to innovative space ventures, enabling still more fantastic space-based telescopes in the coming decades. New light collection techniques taking advantage of the lensing effects of Earth's atmosphere or the Sun's gravitational field have also been proposed [33,10]. Armed with these extraordinary instruments, in the coming decades scientists will peer into the atmospheres of nearby exoplanets identified by wide-field surveys [34] and listen to the sky with still greater aptitude. Additionally, we are developing new and complimentary techniques in characterizing habitable (and, ultimately inhabited) worlds [35].

If, as passivists admit, other civilizations are likely much

older (and thus liable to be much more advanced) than our own, will they not have still more capable telescopes and techniques, and perhaps an interest in using them? Even well-understood technology, scaled to sizes soon achievable, enables remarkable observational reach without resorting to Clarkean maxims. Again, SETI is a two-way street, and passivists fail to apply the mediocrity principle and see humans as extraterrestrial technologists. Theirs is an anti-Copernican viewpoint, arrogating to humans a special reference frame where other ETs' astrobiological signals are detectable, but ours are not. This is spurious. Exoplanets represent natural 'focal points' in the search for technosignatures [36]; Earth is thus liable to be a target of astrobiological scrutiny in the same way other 'potentially habitable' exoplanets have been by humans [37]. Worlds considered habitable that are also bizarre sources of transients (e.g. radar bursts, radio chatter, rapid atmospheric spectral changes, etc.) could be determined to be of special interest, and potential technosignatures that are suspect alone can be made convincing together.

Life has modified Earth's environment considerably through-out its ~4 billion-year tenure on the planet and modeling the detectability of these changes throughout Earth's past (hoping to inform studies of Earthlike exoplanets) has become something of a cottage industry. CH₄ was a thousand times more abundant in the Archean than today; it and photochemical organic hazes derived from it represent two such biosignatures [38]. While the Great Oxidation Event (2.5 billion years ago) knocked CH₄ below plausible detection thresholds and O₂ may have been detectable only for the last ~10% of Earth's history, O₃ discernable through strong ultraviolet features provides a strong proxy for biogenic O₂ since the Paleoproterozoic, stopping the gap [39]. If Earth has been displaying biosignatures continuously for the past 4 Gyrs, then it may be detectable by ETs even at extraordinary distances and through deep time.

In this light METI does not present a unique risk to humankind; those preexisting 'hostile super-civilizations' dedicated to snuffing out other evolutionary experiments in intelligence will have already had considerable time to discover Earth's biotic potential and act accordingly; if they were nearby and wished to find us, they surely could. While some metiists might contend that only intelligent life (or perhaps only those species actively wrecking their planetary ecosystem) would be a cause for aggression, again biosignatures stand as a reliable precursor to technological societies that could provoke such hostility. If these advanced societies are old, as they are likely to be, then it stands to reason that Earth may already be in their proverbial crosshairs.

2.3 Reworking the SETI Paradox

These facts present a dilemma known as the SETI Paradox. First coined by Zaitsev, it is traditionally phrased as 'SETI... is meaningless if no one feels the need to transmit' [40]. It can also be rendered as a question: 'what is the point of SETI if transmission is not worth the risk? We will never find anything!' In this wording, it is specifically unsymmetric 'transmission' that leads to failure of discovery; unfortunately, like Vakoch's formulation of METI's empirical practice, this definition is contrived and narrow. Additionally, it limits itself to the sphere of Communications SETI and relies to some degree on the false claim that passive SETI depends on altruistic messaging. Thankfully, this is not the whole story.

Communications SETI has been likened to a cooperative

game in which players cannot communicate [6]. Framing the SETI Paradox exclusively in terms of transmission buys into the passivist misapprehension that Earth is safe from detection if no interstellar transmissions are sent. The broader view of detectability established herein incorporates METI onto a signaling continuum that includes passively displayed biosignatures and technosignatures, both of which are broadcast merely by our presence on Earth. This makes the larger SETI project an opt-out, not an opt-in game – voiding the traditional SETI Paradox, or at least requiring it to be reframed in proper terms.

If civilizations truly are risk-averse, they will not just avoid METI programs, but also minimize communication leakage, and perhaps not engage in large-scale activity of the kind that would be visible to other ETs. Inordinately cautious ones could suppress atmospheric and surficial signals too, for fear of being found [22]. If all nearby civilizations do this, then none of them will discover each other. This is the reworked SETI Paradox: *SETI is meaningless unless at least one alien civilization chooses not to suppress its own panoply of astrobiological signatures.*

This restores SETI to its base assumptions (that civilizations are detectable both through technosignatures and biosignatures) while treating humans as what they are: ETs that can be detected in the diversity of ways we ourselves search for them. A rephrased corollary follows: what is the point of SETI if *signaling* is not worth the risk? SETI predicates itself on the idea that civilizations will exhibit detectable technosignatures, and life biosignatures (though not necessarily at the same time or in the same place – risk-averse civilizations may transmit from locations far from their homeworld); if any of these signals are not forthcoming, then SETI is pointless.

METI's place as the endmember on Earth's signaling continuum underlies the fundamental incoherence to any pro-SETI, anti-METI position: if no one signals, no one receives; if METI is unscientific, then SETI is unscientific; and if we aren't ready to initiate contact, we certainly aren't ready to receive messages to that effect. Every single viable case against METI reduces to one against SETI: a practice that, while not without controversy, is a well-established scientific discipline. Passivists' lack of imagination in this respect and selective application of the Copernican Principle entails, as will be seen, ludicrous and irresponsible policy recommendations.

2.4 Passivists' Absurd Policy Recommendations

Passivists claim that METI presents a unique, existential risk to humankind and further claim that legal countermeasures ought to be taken against it. Gertz gleefully proposes that transmitters be 'proscribed with criminal consequences' on the national or even international level [16], conjuring up fanciful images of SWAT teams descending on the homes of unassuming ham radio operators. More sweepingly, he proposes to prohibit intentional signaling to extrasolar targets at power greater than a terrestrial TV broadcast. This harkens back to the passivist assertion that such signals are not detectable, which can only be considered reasonable when evaluated simplistically; remember, the numerous technosignatures and biosignatures Earth exhibits alongside its special place in the LWHZ (Liquid Water Habitable Zone) cannot be considered separately. Beyond being arbitrary, this injunction is entirely unenforceable [41], and has several downstream consequences.

Metiists have expressed fear that such prohibitions would interfere with asteroid and planetary radar soundings [12], and

targets of powerful EM transmissions will inevitably be smaller than the beam's distant cross-sections themselves. Gertz anticipates this objection by proposing that such transmissions should be prohibited only when targets occult background stars within 1000 LY [16]. Again, this cutoff is arbitrary and fails to appreciate Earth's long and continuous history of astrobiological signaling. The idea seems workable in principle – but see how willing passivists are to squander and complicate valuable telescope time. Additionally, does this propose to limit and interfere with our descendant's ability to communicate across interplanetary and even interstellar distances [10]? Does this entail a moratorium on lightsail-type interstellar probes, given the massive laser arrays (aimed at or near nearby stars) needed to accelerate them to relativistic speeds? This attitude seems strange, given passivists' enthusiasm for the other doings of Breakthrough Initiatives. Lastly, as Gertz weirdly and straw-clutchingly puts it, METI specifically endangers American national security by transmitting information to ETs who are not in Earth's public domain [16]. Take note of appeal to militarism; it will come back.

Conveniently, Gertz' and other passivists' policy proposals entail no serious change to the status quo. However, as they are loathe to realize, radio communications are not Earth's only brand of technosignature. Haqq-Misra terms passivists' policy position as 'precautionary malevolence' and correctly identifies the next step of their logic to be masking passively broadcast technosignatures [22]. Humankind has done a rather good job of cleaning up CFCs, but other atmospheric pollutants anomalous in oxidizing atmospheres remain, notably ammonia, anthropogenic Non-Methane Volatile Organic Compounds (NMVOCs) and heavy metal particulates derived from smelting and refining practices. Additionally, waste heat from power generation and consumption may in time prove detectable to ETs, alongside the spectral signatures of city lights. Assuming precautionary malevolence, all these things are immense liabilities; shall we curtail the practices that create them to drive these pollutants below any conceivable detection limit? Take steps no nation or environmental group is prepared to make to reduce humanity's spectral footprint, in a world unable to swiftly deal with anthropogenic climate change? The authors' feelings on environmental and light pollution aside, these conclusions are absurd and unworkable, and no mandate exists to enact them; it is in this wise that passivist arguments reduce to primitivist critiques, again a strain of thought as dangerous to SETI as to METI.

Passivist arguments also entail fear that Earth, a smallish planet squarely in the LWHZ and replete with resources 'ripe for the taking,' will be subject not just to SETI, but to general astrobiological scrutiny. Indeed, Earth is far enough from its parent star to be directly imaged by coronagraph-equipped, next-generation telescopes, making this an easy task [31]. Ought we go still further and dedicate our energies to pumping out reducing antibiosignatures like H₂ and CO [42] to ward off the evil aliens? Shall we smother the biosphere to hide chlorophyll's ubiquitous spectral fingerprint? Never mind the consequences, it could be said, 'we're holding the fate of the Earth in our hands!'

There is no end to this slippery slope as there is no escaping Earth's status as a putative subject of SETI. Passivists attempt to square this circle by ignoring the detectability of other technosignatures and arbitrarily propose policy options that sufficiently assuage their worries while sacrificing as little comfort as possible. The scientific community need not credit the alarmist projections of these master hypocrites, and policy-

making based on their fears also would run SETI's funding and credibility firmly into the ground.

2.5 Securing SETI's Funding and Success

Passivist arguments present a serious threat to the larger SETI project's continued funding and support. Since 1993, American SETI endeavors have been forced to derive funding from transient, often philanthropic sources; Yuri Milner's Breakthrough Listen initiative has been a massive boon to the field, but there is no guarantee that such private charity will continue. Passive SETI's likelihood of success at any given time is slim; why pour capital into an effort that is virtually guaranteed not to succeed this quarter, or the next, or the one after? Here opposition to METI is no help. METI marginally increases the likelihood of discovery per unit time, thus (however slightly) increasing the likelihood of returns on investment. Again, the SETI Paradox rears its head: what is the point of SETI if, as passivists argue, signaling is too risky? If donors can complete this defeatist syllogism, the SETI project will never secure continuous funding from private sources.

To restore sustainable funding protected by law, SETI's credibility in the eyes of the public and elected politicians needs to be rehabilitated. This may prove difficult, thanks to a phenomenon known as the 'giggle factor' [23]. Talk of 'aliens' makes people laugh, notably Congresspeople and other funding entities. There is no reason to search exclusively for biosignatures when technosignatures may be easier to find [23], but Congress and other government entities *will not take SETI seriously*. The search for biosignatures has thankfully recovered from this laughingstock status, but SETI has yet to escape it. As a result, technosignatures are often considered separate and apart from (or just as a footnote to) serious astrobiological discussion (e.g. [3,4]), when the distinction between them is far more apparent than real. Gertz urges the National Academy of Sciences to release a study in favor of funding SETI, as its recommendations are often considered authoritative by Congress [16]. One sincerely hopes such an effort would succeed, and there have been whispers of change in the wind – but don't positively expect it.

Too often the laughter at SETI projects is not entirely humorous, and it is passivists' fault that this is true. Passivists wish to find ET asymmetrically; they want to spy, not to contact. While all SETI scientists certainly share the view that SETI advances knowledge both of the cosmos and humanity's place in it, the antipathy and melodrama with which passivists describe mutual contact is not lost on the public. Gertz compares ET detection to catastrophic earthquakes and asteroid impacts, and raises the spectre of interstellar attack [15,16]. Notionally serious scientists fret in print about alien invasion [17]. Hawking compares symmetric contact to imperialism and insinuates humanity is not ready for discovery anyway, two things which he cannot claim to know [19]. They oppose METI despite it being a methodological accelerant, and worry that if discovery does happen, Men in Black will appear to hijack and censor this monumental event [16].

It is well-understood that fear, once spread, can provoke irrational behavior in this context [41]; it was not for nothing that Orson Welles' 1938 radio dramatization of *War of the Worlds* excited some two million people to panic in war-jittery America [43]. Passivists' frightened declarations provoke both honest fear of and cynical derision toward SETI from the public and their elected politicians, who promptly refuse to fund it. Gertz finds this disappointment perplexing, then rather dan-

gerously suggests that SETI eschew funding from the National Aeronautics and Space Administration (NASA) and National Science Foundation (NSF) and instead look to the Department of Defense, explicitly recommending that SETI be treated as a problem of military aggression [16]. Gertz may think himself clever, but this is a Faustian bargain the SETI project simply cannot afford to make.

'The fact that SETI is serious hardly requires defense' [16]. Our present conundrum is the natural outcome of stoking fears of alien invasion, and the dread of ETs as aggressors permeates our culture [23]. This fear of contact, and even of discovery, feeds back into the tribalistic mentality that fuels popular but hysterical films like *Independence Day*. Again, *Star Trek* is no model either; what is needed is a middle path, free of both unrealistic fears and aspirations, that treats METI as what it is – an organic and necessary extension to the SETI project.

3 CONCLUSION

Crucial to that middle path is the admission that contact can proceed in a great diversity of ways; the spans of thinkable neutral, positive, and negative outcomes are equal [22]. Even so, one can dismiss contrived notions like the zoo hypothesis, and recognize that METI does not uniquely increase risk even should our cosmic correspondents be 'hostile super-civilizations.' Offered below are policy options that aim to enhance METI's scientific and social standing, in the hopes of maintaining and enriching the financial integrity and public acceptance of the larger SETI project.

3.1 Policy Recommendations

Excluding the two Voyager probes' Golden Records, interstellar messages to date have been sent using mutually unintelligible encoding schemes and without international consultation, proper feasibility studies, ethical concern for miscommunication or even peer review [13,14,44], a suite of facts that belies metiist's past claims to complete scientific rigor. Indeed, there are no guidelines for METI prior to detection of a reply. Earth is detectable to ETs via its continuum of biosignatures, passive technosignatures, and METI; however, METI represents *the only component of Earth's astrobiological signaling that is entirely under our control*. Those who transmit (or authorize transmission) have complete command over the content, strength and direction of the signal. It is outside the scope of this paper to decide who speaks for the Earth (as opposed to other forms of signaling), but that question is not to be written off by those maverick metiists who claim it is their right to get a word in before everyone else. Here METI reduces to a commons problem wherein the actions of individuals may decide the course of history for all concerned, even if the risk to humankind is slight [24]. As such, those who act on their own may be 'engaged in unauthorized... diplomacy' [16]; it follows therefore that we ought to at least be careful about what we transmit, and discourage individuals from doing so by themselves. A more specific and workable set of guidelines are needed to better enshrine, establish, and standardize METI methodology, and here is where well-intentioned passivists and metiists agree. As it is impossible to prevent unauthorized transmissions, METI guidelines must be written charitably and reasonably, *so that they will be followed*.

Future transmissions' feasibility ought to be thoroughly studied in the style of other scientific ventures in outer space: both specifying all parameters of the message and the instru-

ment used to transmit it, and assessing the message's detectability as a function of ET's technical capacity and receiver attributes. Additionally, this information must be free and accessible to the public; an 'online database containing such descriptions in a standard uniform format' is in order [13]. Great care must be taken to ensure that any room for miscommunication is negligible, that messages not provoke disgust in ETs, and to draw upon a broad consensus of human cultures and locations (and animal communications studies) in assessing a messages' comprehensibility and content [17,44]. The specifics of such best-practices are the prerogative of the extended SETI community to decide and debate internally before any thought can be made of making recommendations about transmission to policymakers.

Following this messaging standardization, a concerted plan for sending transmissions to specific targets and receiving return messages must also be developed. Choosing targets will doubtless base itself on the astrobiological scrutiny of potentially habitable exoplanets detailed herein, alongside nearby and/or anomalous stars (e.g. Boyajian's Star). Receiving messages will entail regularly searching a small area of sky around the target after the minimum time for transmission and return (given by twice the target's distance in light-years). This will not be an undue burden on other targeted SETI searches or all-sky surveys, unless something is detected, in which case rapid, confirmatory follow-up observations by other telescopes will be necessary. Humankind has time, in the intervening decades between the sending and receiving of messages, to construct and engineer the facilities needed for such a fantastic enterprise both on and off Earth. Thankfully, such instruments are being designed and built today. Additionally, in line with pro-

posed guidelines for passive SETI, it *must* be stipulated that any information regarding return messages be made free and open to the public, to better discourage the knowledge and/or content of received messages from becoming a flashpoint for international conflict [45].

3.2 Toward a Cautious Optimism

A change in the zeitgeist is needed; the SETI community must trade the arbitrary and self-contradictory pessimism of passivists for the cosmopolitan hope of escaping the SETI Paradox and participating in an interstellar community. Additionally, metiists ought to drop contrived and unpolished arguments in favor of their position and instead embrace METI's place along Earth's continuum of astrobiological signaling. SETI scientists must work to legitimize SETI in the hearts and minds of both politicians and the public, and the first step towards that is leaving speculation about the outcome of contact behind. To boost the likelihood of discovery and maintain passive SETI's funding, we should exercise every technique available to us – in the hopes of someday making SETI the planetary-scale endeavor that such a rich and informative enterprise deserves to be.

Such a cautious optimism about the SETI project enjoins that the darkness of space is nothing to fear and proposes to send a flare into the void to illuminate the path forward. Detractors of METI are afraid of the dark, yet ought be more afraid of their spectral shadows; moreover, following their fearful reasoning to its logical conclusions results in absurd policy recommendations. If we care for the Search for Extraterrestrial Intelligence at all, we must integrate an active approach – to better ensure both its continuity and eventual success.

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DYNAMIC VACUUM MODEL

and Casimir Cavity Experiments

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This paper will summarize a pilot wave interpretation of quantum mechanics known as the dynamic vacuum model that claims the quantum vacuum can vary spatially and temporally. Some of the recently published findings for this dynamic vacuum model approach are discussed and the implications of these findings lead to some possible new insights associated with the Casimir force phenomenon. This deeper study suggests that there is structure to the quantum vacuum in the Casimir cavity and some time will be spend developing some conceptual experiments designed to detect this structure. Some general sizing calculations related to these experiments are provided to determine the possibility of being able to measure the phenomenon in the lab. Two of the noted concepts may have propulsion related benefits, firstly to provide larger amounts of negative vacuum energy density for the idea of a space warp or wormhole, and secondly as an in-space propulsion system with the ability to push on the dynamic vacuum medium.

Keywords: Vacuum energy, Dynamic vacuum, Acoustic waves, Casimir

1 INTRODUCTION

The Copenhagen interpretation is the dominant point of view taken by the physics community today, and has been so since early in the last century. Stated simply, the Copenhagen interpretation of the physical world at a microscopic level is that the nature of reality is probabilistic and not deterministic. While the Copenhagen interpretation enjoys the distinction of being the favored line of thinking, it is not without alternatives. One of the alternative lines of thinking in the ontological debate of the nature of reality at the microscopic level is pilot wave theory. Pilot wave theories are a family of realist/deterministic interpretations of quantum mechanics that make the conjecture that the statistical nature of the formalism of quantum mechanics is due to an ignorance of an underlying more fundamental real dynamics, and that microscopic particles follow real trajectories over time just like larger classical bodies do. The first pilot wave theory was proposed by de Broglie in 1923 [1] where he proposed that a particle interacted with an accompanying guiding wave field, or pilot wave, and this interaction is responsible for guiding the particle along its trajectory orthogonal to the surfaces of constant phase. In 1952, Bohm [2, 3] published a pilot wave theory where the guiding wave is equivalent to the solution of the Schrödinger equation and a particle's velocity is equivalent to the quantum velocity of probability. A more recent conjecture put forward by the authors [4] considers the vacuum as a form of quantum fluid that can sustain both spatial and temporal variations, that is, a dynamic vacuum. In the dynamic vacuum model, the vacuum fluctuations play the role of the guiding wave, specifically, the vacuum fluctuations (vir-

tual fermions and virtual photons) serve as the dynamic medium that guides a real particle on its way.

In [4], the authors considered a heuristic model of the hydrogen atom. The model consisted of the assumptions of a quantum fluid surrounding the proton, a density distribution of that fluid, and of a velocity field describing the spatially varying speed of propagation of a disturbance in the density field. In this dynamic system, acoustic-like resonances could be established describing the electron orbitals as determined by the Helmholtz wave equation. The authors found that the acoustic eigenfrequencies of the system matched observation with a reasonable degree of accuracy ($\psi 100$ error was $\sim 5\%$). A more recent paper [5] completed a painstaking process showing a deep and explicit connection between the Schrödinger equation and the Quantum potential which led to the detailed derivation of the acoustic wave equation for the quantum medium. That work derives the Helmholtz equation from the Schrödinger equation, and provides the rigorous expectation that the system will thus have eigenfrequencies in the form of acoustic resonances.

In [5], the authors updated the numerical model of the hydrogen atom including an explicit derivation of the density distribution of the quantum fluid around the proton. This derivation considered the electric field around the proton where, following standard practice, the electrostatic pressure is expressed as $P_E = \epsilon_0 E^2/2$ where $E = kq/r^2$ and $k = (4\pi\epsilon_0)^{-1}$. The energy density in the field can be determined by making use of the equation of state relationship between pressure and energy density $w = P/\epsilon$ with $w = 1/3$ for radiation. Using the Einstein mass-energy equivalence, the predicted mass density

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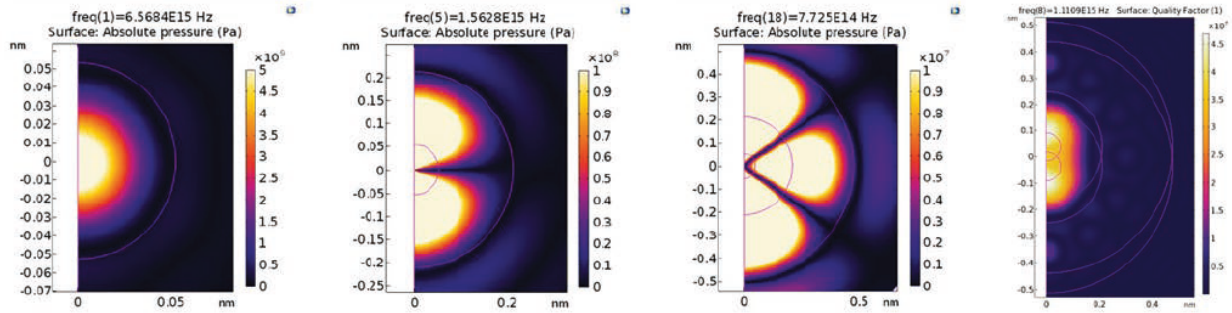


Fig.1: Eigenfrequency pressure distributions from the numerical analysis tool representative of the hydrogen 1s, 2p, and 3d states, and molecular hydrogen.

in the field around the nucleus is quite close to the heuristic derivation relationship derived in the earlier paper: $\rho = 3.06 \times 10^{-46}/r^4 \text{ kg/m}^3$ vs $\rho = 2.99 \times 10^{-46} \text{ kg/m}^3$. The authors found that the acoustic eigenfrequencies of the updated system were closer to observation than in the earlier model analysis results ($\psi 100$ error was $< 1\%$). The updated model approach was also used to assess a two-proton model representative of molecular hydrogen, and the acoustic resonance of the system was found to match observation with similar accuracy as the model results for atomic hydrogen. Fig. 1 depicts some of the acoustic resonances for both atomic hydrogen and molecular hydrogen.

2 CASIMIR CAVITY CONNECTION

The $1/r^4$ dependency of the density field for the quantum fluid from both the heuristic model and explicit model mentioned earlier suggests a possible connection with the Casimir force for a parallel plate cavity. In the Casimir cavity scenario, the “density” of the quantum vacuum has a $1/d^4$ spatial dependency, where the spatial variable, d , is representative of the separation of the plates that define the cavity. One can calculate the predicted average density for $n = 1$ to $n = 7$ states for the hydrogen atom using the $\rho = 3.06 \times 10^{-46}/r^4 \text{ kg/m}^3$ relationship. One can similarly calculate the predicted average density for an equivalent “effective” Casimir cavity where

$$\rho_c =$$

These values are calculated with a ratio provided in Table 1. As can be seen from the table, the ratio of the densities is consistently $\sim 1/3$.

TABLE 1: This table compares the derived “density” of a given energy state n to the Casimir density for a cavity with a separation distance of $2r_n$. The Casimir column is the Casimir force per unit area multiplied by $1/c^2$. The Ratio column is the Casimir column value divided by the ρ column value.

n	radius (m)	ρ (kg/m ³)	Casimir (kg/m ³)	Ratio
1	5.29×10^{-11}	3.91×10^{-5}	1.16×10^{-4}	2.95
2	2.11×10^{-10}	1.53×10^{-7}	4.51×10^{-7}	2.95
3	4.76×10^{-10}	5.95×10^{-9}	1.76×10^{-8}	2.95
4	8.46×10^{-10}	5.96×10^{-10}	1.76×10^{-9}	2.95
5	1.32×10^{-9}	1.00×10^{-10}	2.96×10^{-10}	2.95
6	1.90×10^{-9}	2.33×10^{-11}	6.88×10^{-11}	2.95
7	2.59×10^{-9}	6.78×10^{-12}	2.00×10^{-11}	2.95

Since the density explicitly derived for the quantum fluid is dependent on the electric field of the atom, it has a dependency on the atomic number Z : $\rho = Z \times 3.06 \times 10^{-46}/r^4 \text{ kg/m}^3$. The Casimir density equation can likewise be updated to include this same Z dependency and the $\sim 1/3$ factor identified in Table 1 such that it takes the following form:

$$\rho_c = \frac{Z}{3c^2} \frac{\hbar c \pi^2}{240(2r)^4}$$

Fig. 2 shows a plot of radius versus density for the primary quantum numbers $n = 1$ to $n = 7$ for the atomic numbers $Z = 1$ to $Z = 7$. The density values for the different cases are plotted as crosses and polygons, while the Casimir density is plotted as circles. Trend lines have been added for the different atomic number cases to visually group the related primary quantum numbers.

This intriguing correlation of the density function for the quantum fluid around the nucleus of the atom and the Casimir cavity calculation motivates another consideration. If the Casimir cavity equation can make a prediction for the density in the quantum vacuum around the nucleus, can the density equation derived from the electric field provide a prediction for the shape and structure of the electric field inside the Casimir cavity? Typically, the density of the quantum vacuum within a Casimir cavity is assumed to be isotropic and unchanging, the walls are at the same potential (typically grounded in an

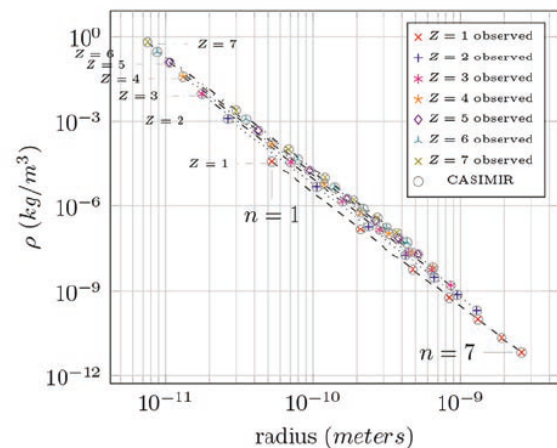


Fig.2 Density of quantum fluid plotted for $n = 1$ to $n = 7$ for $Z = 1$ through $Z = 7$. The bottom line labelled $Z = 1$ represents hydrogen, and labels for the points representing $n = 1$ and $n = 7$ have been added. The Casimir values are also plotted as hollow circles.

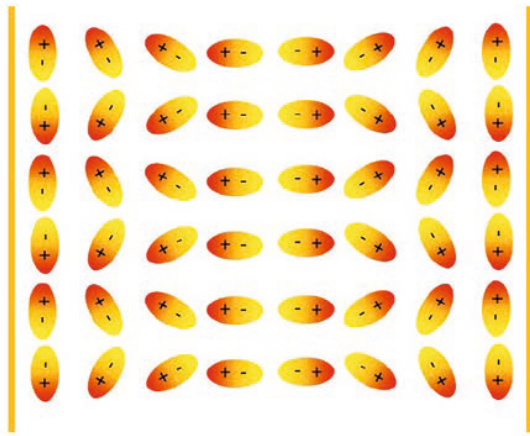


Fig.3 Polarization of the vacuum fluctuations in a Casimir cavity.

experiment), and there is no anticipated electric field expressed in the cavity. However, the case being considered would seem to indicate that this may not be the situation. After a bit of manipulation, an equation that predicts the electric field being expressed in the middle of the Casimir cavity can be shown to be:

$$E = \sqrt{\frac{1}{9\epsilon_0} \frac{2\hbar c\pi^2}{240 \cdot 16(d/2)^4}} \quad (1)$$

The field originates at the midplane of the cavity and extends outward to the plates in an analogous manner to what is found around the nucleus of the atom in the form of the radial electric field. It is conjectured that what may be occurring in the Casimir cavity case is that the vacuum is polarizing in response to the exterior conductive walls being held at the same potential (grounded), and the change in vacuum energy density is a result of the energy density in this polarization field being expressed by the quantum vacuum fluid. Fig. 3 shows a conceptual view of the polarization of the ephemeral fermion antifermion pairs that is conjectured to exist in the cavity expressing the electric field.

3 CASIMIR CAVITY EXPERIMENT

3.1 Case 1: Measuring Effective Electric Field in Cavity

If this conjectured polarization field is present in the Casimir cavity, one can devise some conceptual experiments designed to detect and interact with this field. One fairly direct approach might be to construct a Casimir cavity that includes an electric field probe located along the midplane of the cavity. For example, a probe could be a single whip probe or a fork-like probe that has two or three whip probes. The constraint for the whip probes would be that their cross section would be minimal when compared to the size of the side plates so that their effects on the vacuum energy density are negligible from an experimental view. It should be explicitly stated that the purpose of the experimental setup described here is to measure the electric field, not the Casimir force, so the construction approach used could be a layered lithography type process with the cavity and its elements deposited/etched on/into a substrate. Fig. 4 depicts a representation of the cavity concept with the necessary elements. For analysis purposes to evaluate the viability of the notional experimental setup, the cavity is envisioned to have a separation distance of 1 micrometer. The size of the side plates is 1 millimeter long and 0.2 mm tall. The predicted

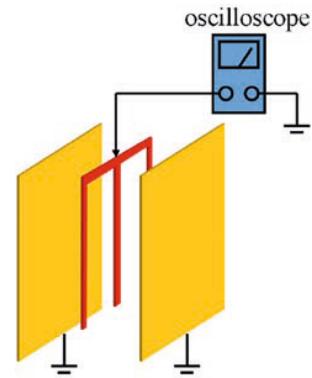


Fig.4 Casimir cavity with whip probes to measure effective electric field from vacuum polarization.

electric field present in the noted cavity is ~ 2.86 millivolts and the total amount of negative energy in the cavity would then be 8.28×10^{-17} joules. If the whip probe located along the midplane is connected to a meter that has a 10 Megohm impedance, the meter will drain the energy in the cavity in approximately 0.1 milliseconds. This magnitude and duration of voltage transient should be detectable by a laboratory oscilloscope.

3.2 Case 2: Increasing Magnitude of Casimir Force

Another approach to explore if there is structure to the vacuum in a Casimir cavity would be to implement an experiment to measure the force between two movable plates defining the cavity. This setup utilizes the electric field probe construction detailed for Case 1, however, in this case the probe is connected to a voltage power supply to maintain the voltage of the probe at a higher value than predicted by Equation 1. For example, if a Casimir cavity of identical geometry as detailed in Case 1 were implemented such that one could measure the magnitude of the force, and the voltage of the probe externally driven to twice the value (2×-2.86 millivolts), then the magnitude of the force is predicted to increase four fold. While there are electrostatic forces to account for in this experimental setup, they are of a different magnitude than the Casimir force, and could be analytically calculated and subtracted from the results. The real challenges envisioned for the implementation of this experiment would be the ability to precisely control alignment of the plates and probe relative to one another, and the ability to accurately place the objects with precision separation distances envisioned. It should be noted that if this increase in force is measured, it would also indicate that the magnitude of the negative vacuum energy density in the cavity has been externally pumped to a larger magnitude.

3.3 Case 3: Tapered Casimir Cavity

Another potential experiment enabled by the insights discussed in this paper is the implementation of a tapered Casimir cavity. A tapered Casimir cavity would induce a pressure gradient in the gap between the plates thus resulting in a force parallel to the midplane of the cavity and directed from the large end to the small end. In order to maintain this force, field probes would be placed in the gap and have external power applied to maintain the pressure gradient thus preventing the flow from simply oscillating. The applied voltage of the probe and taper angle of the cavity could be increased to see an increase in the

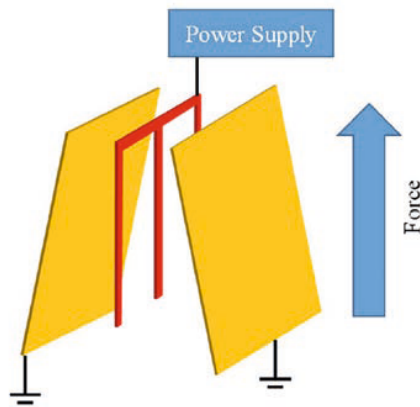


Fig.5 Tapered Casimir cavity with whip probes.

magnitude of the force. Fig. 5 depicts a notional cavity concept where it is anticipated that similar to Case 1, the setup could be built atop a substrate using a layered lithography approach to build up the elements. If the tapered cavity is such that the narrow gap is 2 micrometers wide, the large gap is 7 micrometers wide, the overall length of the cavity is 50 micrometers, and the height of the plates is 0.2 millimeters, then a single cavity is predicted to generate 0.7 piconewtons when 0.1 millivolts is applied to the probes. The thrust to power for this system is quite low at roughly twice that of a photon rocket's performance, so the system may not be useful for generating thrust for any reason other than exploring the physics of the phenomenon. However, the tapered cavity could be arrayed on a wafer in large numbers to increase the power throughput of the system and be a source of longitudinal waves in the vacuum for many and varied applications.

4 PROPULSION IMPLICATIONS

There are some propulsion related implications that may be of interest should the noted experiments detailed in the preceding sections confirm the predicted dynamic vacuum structure in the Casimir cavity. Firstly, the Case 2 experiment envisioned to increase the magnitude of the Casimir force achieves this effect by increasing the magnitude of the negative vacuum energy density that exists between the two plates that define the cavity. As is known in the physics community, the properties of negative vacuum energy density are mathematically equivalent to the concept of exotic matter as it is defined within the framework of general relativity. Indeed, negative vacuum energy density was discussed in one of the earliest papers exploring the concept of a space warp as a viable exotic matter candidate to satisfy the requirements of the field equations [6]. If the Case 2 experiment were able to manifest an increase in magnitude of the Casimir force (and hence negative vacuum energy density), then one could imagine a follow-on experiment that would make use of a very small three dimensional toroidal construction (<1 cm), whose volume is entirely filled with a matrix of these cavities. This small toroid construction could be employed in an interferometer experiment where it is placed along one of the two beam paths allowing the beam to traverse through the toroid opening along its central axis. Increasing the voltage applied to the antennas within the matrix of Casimir cavities discretizing the toroidal geometry would increase the magnitude of the negative vacuum energy density present throughout the ring, and thus would induce a change in optical path length over a spherical domain defined by the toroid's outer diameter for the transiting interferometer photons. A laser source of

photons would be used to create an interference pattern at the detector with the toroidal device off, and then again with the device on. These two interference patterns would be utilized as inputs to some signal analysis algorithms designed to explicitly quantify changes in beam path as measured by the apparatus. An iteration on this approach with more sensitivity would be to pulse/energize the toroid at a fixed frequency (e.g. 4 Hz) while collecting an array of interference patterns from the detector such as a two-dimensional image sampled at say 30-60 Hz. The coherent array of interference patterns could be run through a Fourier analysis algorithm on a pixel by pixel basis to determine if there is energy in the spectrum associated with the drive frequency. This technique could be used to collect longer and longer data samples such that the signal to noise ratio would increase with longer observation times. The pinnacle objective of this experiment would simply be to detect the manifestation of a microscopic warp bubble in the laboratory.

Secondly, an iteration of the Case 3 experiment, effectively a longitudinal wave photon rocket as is, would be to apply an external magnetic field orthogonal to the force vector in an attempt to increase the thrust to power ratio of the apparatus. The application of an external magnetic field to the cavity affects the pressure gradient induced in the dynamic vacuum, resulting in a slower predicted exit velocity of the flow from the cavity whereby increasing the thrust to power ratio. By applying a 2000 Gauss magnetic field, energizing the forks to 40 millivolts, a single cavity is predicted to yield a thrust of 3.67×10^{-11} N with a thrust to power ratio of $6.3 \mu\text{N/W}$ – which is just an order of magnitude below a Hall thruster. One might envision fabrication of a 1 cm x 1 cm wafer equipped with a couple thousand of these cavities arrayed across the surface of the wafer by means of nanofabrication techniques, and this Casimir wafer might be used in a CubeSat as a form of in-space propulsion. This wafer might be stacked to facilitate processing of more power based on the CubeSat mission objectives and power budget. Alternately, higher magnetic fields might be explored to determine if the thrust to power ratio might be made to be more competitive with Hall thrusters.

5 CONCLUSIONS

This paper has provided a brief summary of the pilot wave interpretation of quantum mechanics and provided an overview of a recent pilot wave model approach known as the dynamic vacuum model. Some of the recently published findings for the dynamic vacuum model approach were discussed and the implications of these findings led to some possible new insights associated with the Casimir force phenomenon. The implications that there is structure to the quantum vacuum in the cavity were discussed and some notional experiments were presented. Some general sizing calculations related to these experiments were provided to determine the possibility of being able to measure the phenomenon in the lab. The propulsion implications from two of the noted experimental concepts were highlighted and briefly discussed.

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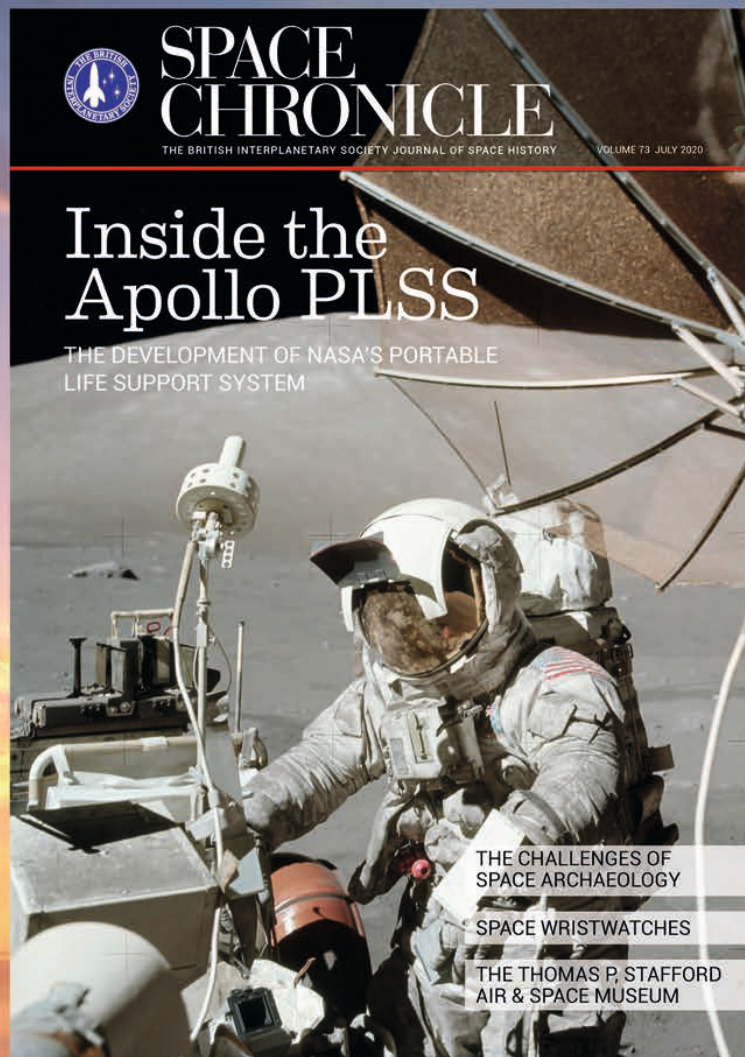
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