Polynesian Colonization as a Model for Human Expansion into the Solar System

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The expansion of Polynesian settlers across the major island groups of the Pacific Ocean represents a substantial human achievement, in that significant distances of open ocean were regularly crossed by hundreds or thousands of people, most likely in small groups. The environment of the Pacific Ocean is a series of habitable or marginally-habitable patches of land scattered amid large expanses of ocean; this is similar to the solar system, which consists of a widespread number of planetary bodies with solid surfaces that offer various potential resources for human habitation including oxygen, water, metals, and even the ingredients for carbon-based fuel and edible material. The process of expansion into the Pacific Ocean by humans likely included multiple episodes of long-distance colonization by small groups; repeated instances of reliable, long-range voyaging between habitable locations were likely enabled by technological advances in navigation and transportation, and sustained by in-situ resource utilization. This is analogous to a possible paradigm for present-day human colonization of space that might include scouting, setup, and scientific missions by professional astronauts, as well as follow-up missions of permanent colonists. Details from historical and archaeological work examining Polynesian expansion may prove to be a source of insight into ways in which the path of permanent human expansion from the Earth might develop. This paper proposes to identify several means of leveraging these details into insights, including a concentrated analysis of the relative land areas available to exploring groups, technology required to enable distant settlements, and the investment required to support such endeavors. This paper also compares historically-attested constructs for far-flung settlement in the Pacific Ocean, including distant trade networks, with possible future analogues in the solar system (e. g., multi-asteroid mining colonies). The relative impetus of technological, societal, and other factors in both ancient Polynesian and modern society is introduced as a primary topic for future work.

Keywords: space colonization, history, society & aerospace technology.

I. Introduction

CULTURAL analogies for human expansion into space usually focus either on the discovery of the New World by the western European powers in the late 1400s and early 1500s or alternatively on the Roman expansion across Europe in antiquity, which sowed the seeds of western European civilization. While these analogies are helpful to understand historical examples of the extension of a civilization and the assimilation of new territories and resources, the authors posit that the Roman Empire and imperial European expansions may not be the most appropriate examples for informing future expansion of human civilization into space.

While both examples feature an expansion of a civilization and a culture beyond common experience and customary trade routes to previously unknown or far-flung regions, both share certain traits that decidedly divorce them from the circumstances facing humanity today in colonizing the solar system. Both of these examples involved

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the colonization of large, essentially contiguous landmasses, which were both rich in resources useful to humans and already occupied by people. These situations make a viable analogy for spreading human presence across a new planet with a relatively hospitable environment, but spreading human presence across the solar system (and without substantial terraforming or other extreme, as-yet futuristic technologies) will entail accessing a wide range of bodies, spread across a large variation of distances, with a wide range of environments, and harboring no known prior residents.

There is, however, an episode in human history containing an expansion surprisingly similar to our current situation; this episode witnessed people crossing long distances of hostile environment using advanced technology to settle sometimes-marginal environments with small groups of humans. This episode is the prehistoric colonization of the Pacific islands, especially those in Far Oceania, by the ancestors of modern Polynesians. The process of expansion into the Pacific Ocean likely included multiple episodes of long-distance colonization by small groups that relied on technological advances in navigation and transportation, as well as the efficient utilization of resources provided by the sea and destination islands.

The prehistoric Polynesian example is analogous to a possible paradigm for present-day human colonization of space that might include scouting, setup, and scientific missions by professional astronauts, as well as follow-up missions of permanent colonists. This exploratory paper seeks to identify prominent historical parallels between prehistoric Polynesian expansion into the Pacific and the modern day expansion of humanity into the solar system; the purpose of this exploration is ultimately to inform future decisions relating to planning and executing space colonization from the successful example provided by the rich tradition and history of Polynesian culture.

II. Polynesian Expansion

The settlement of the Pacific islands occurred in two main phases, separated by a gap of several thousand years. The first phase covered the region known today as Near Oceania ("Near" referring to its relative proximity to the Asian landmass), and took place starting around 40,000 years ago. This preliminary phase featured the settlement of intervisible islands, or landmasses that could be sighted from an already-established settlement. The later expansion, across Remote Oceania, began in perhaps 1500 BC and lasted until about AD 1000-1400. This period of expansion featured longer voyages across open ocean, often to destinations that were beyond the horizon.[1] The actual historical geography of human expansion is likely very complex, with technological and genetic interaction between those who explored and settled in various Near Oceania islands and those who sailed afield to Remote Oceania. Despite this complexity, and although the expansion of the Polynesian people across these islands most likely occurred in stages and with much backtracking, it is still possible to trace some features of the expansion today.

Expansion across the Pacific islands specifically in the latter phase of Polynesian expansion can be traced by the spread of technology including canoes and masts for sails, fishhooks, obsidian hand tools, and pottery across various islands in Remote Oceania[2]. Biological evidence of food sources including chickens, pigs, and agricultural products at a broad range of sites in Near and Remote Oceania alike reveals the introduction of non-indigenous plants and animals, most likely to serve as food sources, by human settlers in the same regions[1,3]. Finally, genetic analysis of modern-day Pacific islanders supports a theory of directed settlement rather than a more randomized or natural-disaster driven expansion. For instance, the genetic diversity of Maori in New Zealand suggests a founding population size of 100-200 humans there, about half of whom were female. The demographics of this proposed population suggest a directed settlement rather than a random happenstance, and intriguingly are approximately consistent with local oral tradition regarding settlement[4].

In addition to the "transported landscapes" of plants, animals, and fishing gear the oral tradition of the Polynesians reveals a key to their incredible range of exploration and settlements beyond evidence of canoe and sail technology: weather knowledge and navigation schema. Appropriate weather knowledge consisted of the understanding that seasonal easterly winds give way to the westerly trade winds around the same time of year. This knowledge allowed for a strategy of upwind exploration during period of countervailing breezes, followed by an assured way to return home[5]. Navigation technology, based on the use of stars and a complex understanding of their motion, ocean currents, breezes, and other factors, is worth many other discussions in itself (for instance, see Reference 6), undoubtedly played a prominent role in Polynesian expansion. Corroborating oral tradition is an analytical study by Levison, Ward and Webb, who showed with a computer simulation that drifting and natural weather was an unlikely driver for observed human colonization and that instead a concerted intent to voyage is a more probable cause.

It is not the focus of this paper to fully describe the history or origin of the Polynesian people, but rather to provide a new perspective from which this knowledge might be viewed. The goal here is to introduce this new viewpoint to aid the present and future task of establishing a lasting and flourishing human presence in the solar system and beyond. For the reader interested in learning more about Polynesian history, see References 7-9.

III. Land Opportunity, Enabling Technology, and Investment for Human Expansion

Archaeological, biological, and cultural evidence described above points to a concerted human effort to settle the Pacific islands, despite the great and inhospitable distances separating landmasses. How does this expansion compare to our present and future task of expanding a lasting human presence in space? And how might we quantify these comparisons in order to learn what opportunities or requirements may lie in store for us? Three approaches to make headway on these problems include: 1. a comparison of available land, quantified by surface area of target destinations and associated transit time to reach these targets; 2. the identification of enabling technology that provides the means for transport; and 3. an evaluation of investment required to mount exploratory and migration voyages in terms of people-hours or budget allocation.

A. Quantifying Expansion with Land Area

A comparison of the extent of landmass available to settlers constitutes an important parallel between the past and present scenarios for human expansion endeavors. Historically, humanity has eyed Mars as our future home, to be colonized in addition to the Earth, enabling further growth in industry and population as well as contribute to our chances of long-term survival as a species. Even though Mars may be the largest rocky body aside from Earth in our solar system that we know about, there are many more small rocky bodies dispersed in the solar system. With sufficient technological advances (to be discussed in the next section), these too may become attractive targets for exploration and settlement.

Considering that the total habitable land area on Earth is around 149 M km^2, while Mars has around 144.8 M $km^2$of land, the whole enterprise of the Age of Exploration in the time of Columbus (which saw the addition of roughly 71.5 M km^2 to the Known (Old) World's landmass surface area of roughly 63.7 M km^2)[‡] might be considered analogous to a landing on Mars, followed by a sustained colonization effort. But this could just be one step in our journey beyond the surface of Earth. There are around 25 moons of 100 km or more radius that are currently known[10]. If we accept 100 km radius as the limit of human habitation (depending on the moon's composition this is around a thousandth of Earth's gravity), we have about 107 M km^2more land to consider beyond Mars. Even if we use ~730 km as the cutoff radius (roughly the mean radius of the moon Iapetus, the third-largest moon of Saturn), corresponding to a gravity of ~2% of Earth's gravity), the usable land area we are provided reduces to ~100 M km^2. This leaves a whole separate "New World" in addition to Mars scattered among anywhere from 10 to 25 new locations, from our moon Luna to the asteroid belt and to the moons of the other planets.

The ambition to establish a sustained human presence beyond Earth entails the colonization or utilization of varied, small planetary bodies stretched across vast empty distances. Unlike in the ancient Roman or the colonial European examples, the geographical distribution of ancient Polynesian settlements closely approximates the distribution in our solar system of rocky bodies. That is, the Pacific Ocean is a region of many small, varied, and far-flung patches of human-habitable land, as might be compared with the very large, continuously-variable but still habitable American continents in the centuries of exploration following Columbus or in the Mediterranean and surrounding regions of the Roman Empire's expansion. A final reason that the Polynesian example more closely resembles our space settlement ambitions is that the Polynesian expansion into the Pacific invariably witnessed first contact with never-before-seen parcels of land, uninhabited by humans. This, of course, differs from the American and Roman examples in which the expanding civilization colonized previously-inhabited lands.

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‡ The total area of Eurasia is around 54.8 M km^2, and Africa is 30.2 M km^2, per Reference 11. However, assuming that only North Africa (8.9 M km^2) counts as "known" and well-explored in Columbus' time, the known area of the Old World was about 63.7 M km^2. The total land area of the New World (some of which, admittedly, remained as unexplored as central Africa for some time, but which we may assume would all have been equally unknown at the time of its discovery) was about 24.7 M km^2 for North America and 17.8 M $km^2$for South America, or 42.6 M km^2overall. Notably, there remained a further 7.7 M km^2 of Australia and 14 M km^2 of Antarctica yet to discover, for a total of 21.7 M km^2 of unknown continental land. Assuming only North and South America, sub-Saharan Africa and Australia were land masses that were "unknown" and habitable at the time of Columbus, a total of 71.5 M km^2 of land area remained to be discovered, as compared with the 63.7 M km^2 of known land area.

Figure 1a depicts the distribution of landmasses in the Pacific with the exception of Australia. Land area of Pacific islands in this plot is referenced to the surface area of Taiwan, and the transit time to reach Pacific islands from Taiwan is calculated by assuming a straight-line approach with canoe speed of 8 km/hr. This also does not account for specific sailing paths, currents or wind patterns, and other factors, but gives a general picture of the relative distances.

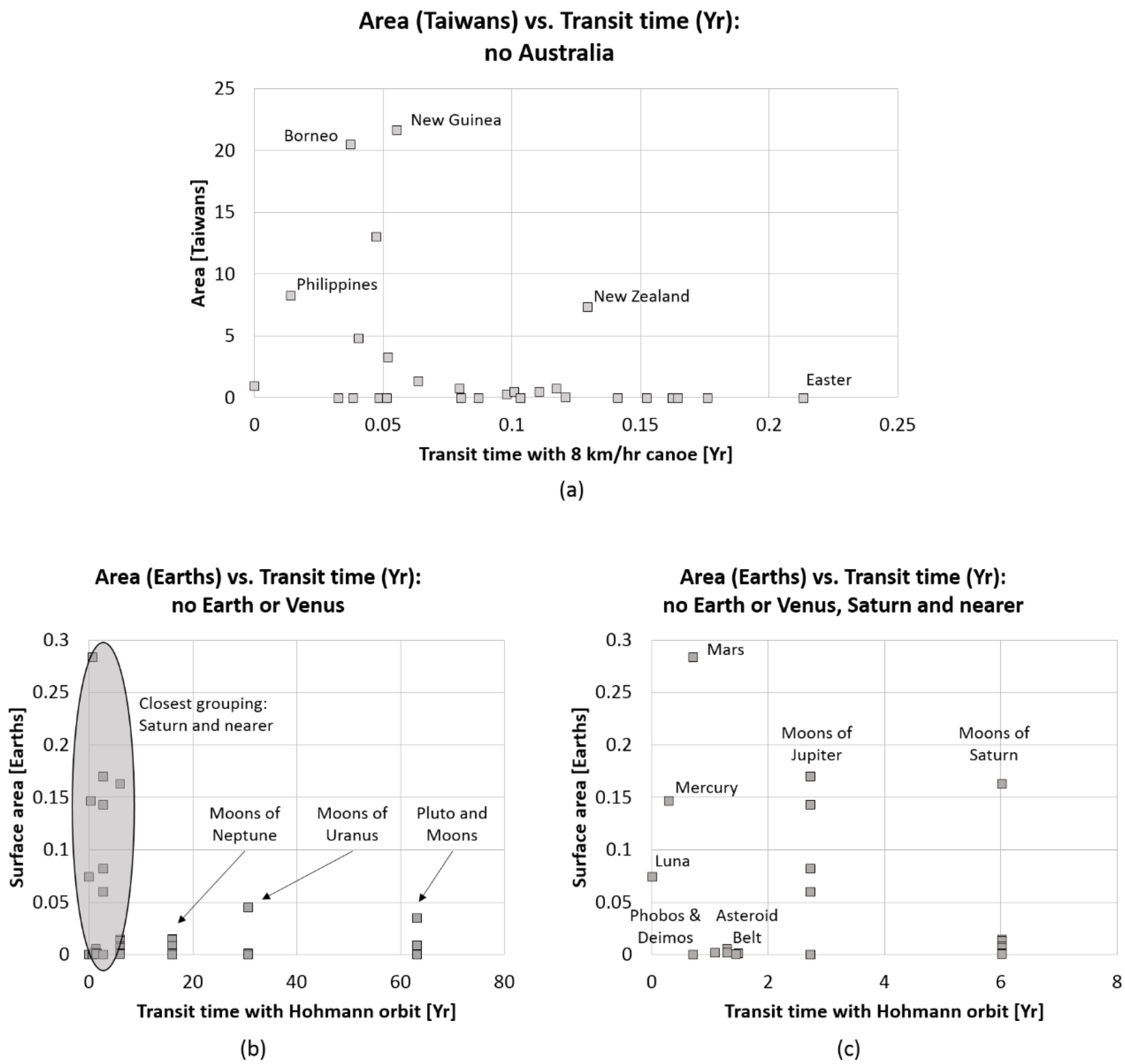


Figure 1. Quantitative comparison of land area vs distance as measured by transit time. (a) Land area distribution from the perspective of pre-historic Polynesians beginning on the island of Taiwan; (b) Land area distribution of potentially habitable rocky bodies in space as a function of mean distance from Earth; (c) zoomed perspective of planetary distribution depicting bodies out only to Saturn's neighborhood.

Figure 1b depict the distribution of potentially habitable landmasses in our solar system. Planetary bodies shown include those with solid surfaces (Europa is included) with the exception of Earth and Venus (Venus dominates the plot, though the planet's surface may be uninhabitable due to its dense atmosphere). Instead of referencing the land area of Taiwan, the surface area of Earth is used as a unit of area. The Hohmann transfer time from Earth to the solar distance of that body is used as a proxy for transit time. This does not account for maneuvers needed to make orbit of moons around gas giants, perform entry, descent, and landing, nor the timing of the voyage or inclusion of gravitational assists, but does give a general overview. Finally, Figure 1c shows a zoomed perspective of rocky bodies in Earth's neighborhood extended to the Saturnian system only.

Note in the Pacific island plot (Figure 1a) that there are some small and large sites close to Taiwan as well as some sites that are very far (Easter Island, Henderson archipelago) but not quite worth it, and some very far but worth the travel (Hawaii). Similarly, in Figure 1b there are small bodies distributed far from Earth but also significantly-sized bodies in the Jovian and Saturnian system that may prove to be worth traveling to despite long transit times. Aside from the nearby Luna, Mercury and Mars, the Jovian system shows perhaps the largest potential in terms of the amount of rocky surface area within transit distance that may support colonization activities.

The Polynesian expansion across the land bodies depicted in Figure 1a was often carried out in multiple small trips over shorter intervening distances. It is highly possible that eventual human expansion into the entire Solar System (Figure 1b and 1c) will resemble the Polynesian model of incremental network building and outpost settlement as compared with a Columbia-era colonization effort. For instance, the Kuiper Belt may well be settled from the surface of Mars or the outer moons of the gas giants, rather than from comparatively-distant Earth itself. Of course, the implication is that solar system settlers will be able to sustain themselves with resources like water and carbonaceous compounds on distant bodies, and otherwise ensure survival by harvesting materials and energy for habitats, environmental and life support, propulsion, and other vital subsystems required to support mobile human operations in space. For those communities in a region with more of one type of resource than other vital resources, trade will be necessary to strengthen the quality of life, if not to support larger communities than might otherwise be sustained in a resource-limited rocky body.

A concern that may be brought up by the comparison depicted in Figure 1 is that the transit times for the solar system perspective in Figures 1b and 1c are significantly longer than the transit times required for island hopping in the Pacific. With advanced propulsion these transit times may be drastically shortened, and with advanced environmental control, life support system, and food technology, longer in-space voyage time than may otherwise be considered practical can be introduced. In order to more fully understand the role that technology plays, the next section compares enabling technology in the Polynesian and in the space colonization cases.

B. Technology Required for Expansion

The area known today as Wallacea in Near Oceania was settled by humans who most likely engaged in water crossing between intervisible islands, and thus spread throughout the region without ever leaving sight of land. It has been hypothesized that this kind of voyaging may eventually have grown into the development of the open-ocean sailing canoe about 3500 years ago[5]. The presence of intervisible islands may have served as the impetus for the original development of technologies that later were used in the creation of an ocean-exploring enterprise – for instance, the use of handheld adzes to create dugout forms and the concept of outriggers for stability, among others. This is perhaps analogous to the way in which the 1960s-era low-Earth orbit experiments led to human landings on the Moon (Luna). Lunar landings may have in turn driven the development of technologies that may one day serve as a basis for sending humans to Mars or the moons of the outer planets.

In ancient Polynesia, key technologies needed to support long-distance travel between Pacific islands included specialized, non-walking, non-ancient mobility technology, adjuncts to mobility technology including specialized celestial navigation, and technologies permitting humans to survive in marginal environments for extended periods of time; in this case, this category of technology would include careful culturing of plants and animals for food sources, and the harvesting of local resources for repurposing into additional technology, as well as the collection of rainwater and fresh fish along the way to a destination to supplement specially selected food suitable long-duration travel.

A list of critical technologies both for Polynesian settlement of the Pacific and for the future human settlement of the solar system includes: propulsion, navigation, resource management and in-situ resource utilization (that is, making use of resources collected at a destination or along the way such as collecting rainwater or fishing in the case of Polynesian explorers), as well as the establishment of infrastructure or communication necessary to support viable trade networks. While each of these technology areas can be investigated in detail, this paper selects propulsion as a preliminary focus for evaluation and elucidation.

Early efforts by Pacific archaeologists established a baseline for comparing various methods of crossing the great intervening distances between islands[12]. Because drifting with ocean currents is infeasible due to the scattershot resulting directions of motion, some method of directed propulsion is clearly necessary for successful colonization purposes. In 1966, Finney and Horvath built a reconstructed ancestral Polynesian canoe, which was followed in 1992 by an effort to cross 1387 km of open ocean by paddle propulsion. While the crossing was successfully conducted, it was necessary to bring an escort vessel to provide for adequate crew supply and shelter availability. This was necessitated by the fact that paddling is calorie-intensive, and creates a significant need for food and rest, while at the same time paddling is affected by the total cargo mass of the vessel, and thus carrying additional food and shelter materials creates a need to either paddle harder or longer, resulting in a feedback loop.

Accordingly and intuitively, wind propulsion via sail is a far more effective method of transiting oceans that is paddling. This is an example of an enabling technology being a prerequisite for exploration - in this case, a form of advanced propulsion technology. We can examine the technology of sailing canoes for insights into the role they played in enabling human expansion. Replica canoes, including the 1975-built Hokule'a as an example, can be up to 19 m long, with 2 masts and 50 m^2 of sail. The Hokule'a required two years to build and about a year of sea trials before sailing, and can reach speeds of 12 kph on average (with 22 kph peak). It is speculated that canoes built in the 1700s, at the peak of the technology's use, could hit up to 31 kph peak, although 4 kph is a much more reasonable average over an entire voyage.[§]

Interestingly, the use of sailing canoes as a primary means of transit suggests a critical limitation on the system: trees that produce trunks big enough for masts to carry sail must be available. While this has implications for the case of heavy industry on resource-poor asteroids attempting to settle nearby moons, the solution is as apparent now as it was then. Trading networks to carry limited key resources from point to point, as could be the case in the future asteroid belt, were already in place in the Carolines to distribute limited resources across a comparatively widespread regime of human activity and spatial geography.

The transition to sailing from rowing is equivalent to a necessary transition to advanced propulsion systems that are capable of drastically reducing the transit times listed in Figure 1b and Figure 1c, for instance. Nuclear-powered electric propulsion is a leading candidate for short-term improvement to our propulsion capabilities, but even these very high-powered systems rely on the ejection of fuel for thrust, a basic limitation of any rocket. With long travel distances and a desire to limit transit time, though, the requirement to carry along all the fuel that is required for maneuvers becomes overly burdensome, effectively making such a mission impossible.

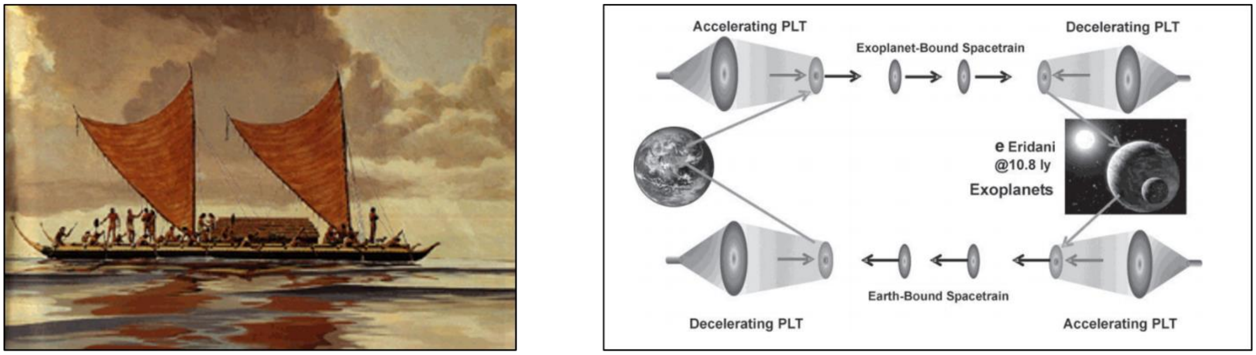
One route to the advanced propulsion breakthrough equivalent to the Polynesian's introduction of the wind-sail would be to establish a network of fuel-manufacturing outposts that might relieve the fuel-carrying burden of long-voyage spacecraft. It is now common knowledge in the space community that water is a resource that can be found all over the solar system, from the poles of Luna and Mars, to asteroids and comets, and to the Jovian and Saturnian moons including Europa and Enceladus among many other documented cases. Water can be mined in the form of ice from rocky-body outposts by autonomous or tele-operated robotic spacecraft to replenish consumable water supplies; in addition, electrolyzing water into its constitutive components can provide hydrogen and oxygen to re-fuel passing spacecraft.

Another option entirely is to eliminate the need to solely rely on rocket propellant and instead utilize a network of space-based lasers to beam power to spacecraft along their voyage. This concept relies on photon pressure, or the non-zero force that a particle of light applies on an object when absorbed or reflected.[**] Propulsion using externally-beamed photons is a concept explored by many over the years; one particularly insightful implementation of this concept can be found in literature provided by Bae[16] and sponsored by the NASA Innovative Advanced Concepts (NIAC) program through two Phases to date[17].

In Bae's concept, highly focused laser light is directed toward a spacecraft either to accelerate the spacecraft on its journey away, or to decelerate the spacecraft once it has reached its destination. With enough photon reflections, an arbitrarily high speed can be attained, while the spacecraft structure and living quarters are not constrained by the need to also house fuel or energy sources dedicated to main propulsion.

[§] Note that the average canoe speed of 8 km/hr used in Figure 1 and the land area analysis of the previous subsection can be found by averaging the predicted average canoe speed, 4 km/hr, with the experimentally demonstrated average speed of 12 km/hr.

[**] For the curious reader, the momentum p of a photon is equal to the photon's energy E divided by the speed of light c, i.e. $p = E/c$. This comes from the expanded relation $E^2 = p^2c^2 + m^2c^4$ from which Einstein's famous $E = mc^2$ is derived; note that a photon is massless, so the second term of the expanded relation is dropped, leaving just $E = pc$.



(a) (b)

Figure 2 Enabling Technologies. (a) Portrait of an ancient Polynesian canoe by Herb Kawainui Kane, courtesy of PBS[7]*; (b) Proposed photon rocket and sail concept "Photonic Railway" enabled with Bae's Photonoic Laser Thruster (PLT). In Reference 16*, *a proposed infrastructure of high power lasers in space apply photon pressure either to outgoing or to incoming spacecraft to enable high-speed interstellar or intra-solar system travel. Figure courtesy of Bae*[7].

Figure 2 shows images of two enabling propulsion technologies side-by-side. On the left, in Figure 2a, the ancient Polynesian canoe is depicted in a portrait by Herb Kawainui Kane, an artist and historian that provided the image to PBS for their special entitled "A Pacific Odyssey: Polynesian History and Origin" [7]. On the right, in Figure 2b, the Bae "Photonic Railway" concept for externally-beamed momentum for the purposes of breakthrough propulsion within our solar system and beyond to enable human interstellar travel to surrounding solar systems. Both concepts feature externally-powered propulsion to facilitate faster cruising velocities that would be possible with on-board resources alone (paddling in a canoe or conventional chemical, electric, or photonic thrusters on a spacecraft that rely on on-board fuel or energy).

C. Assessing Investment for Expansion

An instructive comparison can be made between the relative costs of fitting out an oversea exploration voyage (on the Polynesian scale) and the total aggregate productivity of the group which performs the fitting out and launches the voyage. As a first-cut approach to assessing the investment required for expansion, the details of construction for a canoe appropriate for exploration voyages is considered. The book *Vaka Moana* provides a detailed overview[5] that has been adapted for the purposes of this assessment.

Canoe building included a sail woven from pandanus leaves, one or two short masts to support the sail, and a dugout hull (the length of which could reach up to 20 m long in ancient vessels). To these we can add structural members such as strakes and front/end hull pieces, caulking/sewing/coating for existing pieces, rope production (from coconut fiber), the rudder, and paddles. This is an approximate listing of the major elements required to build a large oceangoing canoe. Assessment of the fitting-out costs can be done by estimating the hours of labor required to construct each individual segment, assemble the segments, and perform checkout and stocking of the finished vessel.

As an example, if the main body of the canoe were a 20-m tree trunk converted into a hollowed-out hull, we may estimate that 75% of the trunk's total mass must have been removed via strokes of a hand tool (such as a stone or shell adze). If each stroke is assumed to remove a strip of tree trunk material of 25 mm width, 60 mm length, and 3 mm thickness, then we can estimate the volume of material removed with each stroke, and consequently the number of strokes required to remove a full 75% of the trunk's mass. In this case, it comes to 5.89 million strokes. If we assume a reasonable amount of time is necessary to perform any one stroke, then we can arrive at an estimate of 1636 person-hours required to construct this segment of the vessel.

The table below shows this analysis applied to each component of individual element construction.

Work component	Size and method	People-hours (p-hr)	Notes
Main body - hull	20 m, 75% removed	1636	
Main body – prow	1-m cube, 75% rem.	46	
Main body – stern	1-m cube, 75% rem.	46	
Main body – siding	Split 20-m plank, one for each side	56	Split at 25 mm/min, remove 25%
Outrigger		892	Half of main body effort
Masts	3 mm x 25 mm strokes along 0.5-m circum/6-m length	24	44,000 strokes for each of 2 masts
Add'l beams/strakes/ribs	4 per each m length of canoe; each 1 m long and needs 60,000 strokes	200	
Sail	50 m^2, woven at 2 hr/m^2	100	
Water sealant	8 p-hr/L * 1 L/canoe m of length	240	20 canoe, 10 outrigger (m equiv.)
Part Crafting Total		**3240 p-hr**	
Assemble sides and body	2 persons * 2 hr/ m of canoe	40	
Assemble outrigger		40	Same labor as main body
Assemble masts/sail		20	
Add strakes/ribs/etc.	1 hr of labor per m of strake/rib	80	
Sealing	0.5 p-hr/m	10	
Final finishes		20	
Construction Total		**210 p-hr**	
Sea trials	5 crew * 3 trips * 10 hr/trip	150	
Food/material collection for 12 settlers	1 ppl * 60 days * 4 hr/day	2880	Assumes 4 hr/day required to prep one person's food/materials
Food/materials stowage		20	
Final Prep Total		**3050 p-hr**	
GRAND TOTAL		**6500 p-hr**	

Accordingly, we arrive at an aggregate estimate of 6500 person-hours of labor required to outfit and prepare a n exploration voyage. (Note the assumption that sufficient supplies for 60 days of survival – this reflects a 30-day voyage (which is an upper estimate), with an additional 30 days of supplies to establish the explorers on the new settlement before they become self-sufficient.)

We may estimate the total productivity for a small island community of 300 persons as a typical example of the type of settlement which may have launched an exploration voyage. Of these 300 residents, some will be elderly and some will be young; others may be infirm; some will be occupied in leadership, religious, or other roles which do not directly produce goods but which are nonetheless necessary for a functioning society – navigation experts are an example of such a role. Nevertheless, we take the material productivity as consisting of the labor of 100 persons in the community working for an average of 8 hours per day. This produces over a 365-day year a total of 292,000 person-hours of production.

The outfitting of an exploration voyage may then be seem to consume around 2.27% of the community's annual output. This portion of total output is comparable to the fraction of the US federal budget spent by NASA during the 1965 and 1966 spending peak of the Apollo program (2.21%, with succeeding and prior years being lower) [13]. Thus we may note that, for a small community fielding about one major exploration voyage per year, the total fraction of their effort required is comparable to the peak fraction of output the US government devoted to its one major exploration program to another planetary body.

Although there are several layers of assumption in play for this analysis, we may note that this first-order analysis produces results that are at least remarkably close, and that there is surely more of a lesson to be extracted from the comparison of these two values.

IV. Conclusions and Path Ahead

This paper has endeavored to introduce the expansion of human presence throughout the uninhabited expanse of islands in the Pacific Ocean by ancestral Polynesian seafaring people as a model for, and area of study related to, the future expansion of human presence into the entire solar system. The paper highlighted several potential key parallels between the pre-historic Polynesian expansion and human expansion into the solar system: the availability and distribution of land, the time and economic investment required to mount an exploration and settlement effort, and the types of technology that enable such activity. Future work along these lines has a broad range of topics to tackle, including the socio-political and economic incentives for expansion, specific guidance for technological development paths, and the potential importance of commercial trade networks responsible for rapid, sustained growth and expansion, as well as sustainment of remote or partially-isolated colony networks. A few major areas of potential future study are highlighted in the following subsections.

A. Possible Cultural Factors

In pre-historic Polynesia as well as in Europe in the 15th and 16th centuries, and even in the colonial nations of the 18th and 19th centuries, certain cultural conditions obtained, some of which were necessary to enable the sustained spread of people to new lands. At the very least, the socio-political and economic climate must have been conducive to emigration away from a homeland to outposts and early settlements. Combined with this, there must have been financial or personal incentives to move, perhaps a perceived opportunity for life improvement. Finally, the technology and resources available to individuals, communities, and organizations must have been sufficient to provide people the means and capacity to make the trek safely and with a reasonable chance of success at their destination.

Some of these expansions in the more recent past may have occurred at times of high relative social stratification and unrest, and further investigation into the relationship between social upheaval and outward-focused expansion may prove instructive (it is notable that the era of the Apollo program is also considered an era of social change in the United States).

B. Major Lessons Extractable from Historical Study

Some aspects of human expansion may recur across various eras of expansion. For instance, while very many habitable or nearly habitable land areas in the Pacific were settled, it may not be possible to sustain settlements in marginal regions (for example, resource-poor asteroids) without extensive support from connecting trade networks. Additionally, the size of small islands often means they are close to both land-based food sources (such as small animals and plants) and sea-based food sources (including fish and shellfish). The use of 'edge environments' to glean resources from both solid surfaces and surrounding regions (which in a space-based analogy translates to using solid surface materials and solar power in tandem) may prove an enabling factor in settling marginal environments.

C. Eras other than the Renaissance

One of the most interesting factors of the New World colonization by Europeans and the Polynesian expansion is the necessary reliance on technology. While humans spread throughout the entirety of the Old World (and the New World, following transit over the land bridge) by walking or riding, it was not possible for Europeans to reach the Americas, or for Polynesians to reach their islands, without the use of technology, specifically sailing technology. Interestingly, after initial settlement on the Americas, it then became possible for humans to reach nearly the farthest reaches of the new environment by relying on walking or riding technology again, but the geography of Polynesia resulted in a need to rely continually on other forms of mobility technology for continued expansion.

This inherent characteristic suggests two things: the particular way in which ancestral Polynesians relied on advanced technology to expand their presence across the globe may be similar to the ways in which modern humans will use advanced technology to expand beyond the globe; and there are other eras of history than the Renaissance-era voyages of exploration (Christopher Columbus' voyage, most notably) that may serve as very valuable models and analogues for future voyages into space by large numbers of humans.

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