Worldship and self replicating systems

Michel Lamontagne

Michel Lamontagne is a bit of a "Renaissance Man" - visionary, artist and practical engineer. He was the co-leader, with Robert Freeland III, of the Icarus Firefly design study for an interstellar probe propelled by Z-pinch fusion, see *To the Stars in a Century: Z-Pinch fusion & Firefly Icarus* by Patrick Mahon in Principium 22. He is a renowned imaginer of both spacecraft, including Firefly on the cover of Principium 22, a worldship fleet on the cover of Principium 30 and a worldship interior on the cover of our last issue P31. Here he considers the requirements for worldships and a worldship-building society and concludes that worldships can be a relatively early part of a society beginning to occupy the solar system with little impact on its economies or ecosystems.

More about Michel in the brief bio at the end of this article. All otherwise uncredited images here are, of course, credited to Michel Lamontagne.

Summary

The recent publication of Worldships, Feasibility and Rationale, by A Hein et al [1] has redefined some of main parameters of Worldship design, in particular a target population reduced from 100,000 [2] to 3,000, and raised the issue of their viability as an interstellar settlement system. In two other recent papers, Hein, Borgue et al also explore the ideas of self replicating probes and of the artificial Intelligence required for Interstellar vehicles [3][4]. We suggest that these ideas can be combined into a proposal to build Worldships using self replicating factories. This should reduce the cost of Worldships considerably, making them more interesting for a future interplanetary civilisation. The Worldships, due to their large mass, can themselves carry self replicating factories, allowing for the construction of new Worldships and space settlements at the target star system, rather than attempting to terraform any eventual planets found there. This increases the available targets for Worldships to practically every single star in the sky.

Image 1- Worldship with rotating habitat

Worldship parameters

For this article, we chose an average travel velocity of 1% of the speed of light, giving a travel time of 100x the distance in light years. So 430 years to Alpha Centauri. As proposed by Hein et al [1] the minimum acceptable target population for communities to survive such a trip is 1,000 individuals per community, with a total population of 3-4,000 people in one or more Worldship(s). Many small ships are more secure than a single large ship. With the minimum population of 1,000, the 3 or 4 vessels in the Worldship fleet would mass about 12 million tonnes each. Fusion propulsion with an exhaust velocity of 10,000,000 m/s using deuterium or deuterium/He-3 gives us a mass ratio Vo/Vf of 3.3:1. This includes all the propellant required for a continuous thrust system, with both acceleration and deceleration. The Worldship habitats are the main mass of the ship, with over 98% of the ship's mass, mostly in the form of radiation shielding and structural components. A large part of the habitat mass is also taken up by the biome in the habitat, mostly in the air, soil and water. The human passengers represent only about 100 tonnes, a tiny fraction of the vehicle's mass.

Worldship description

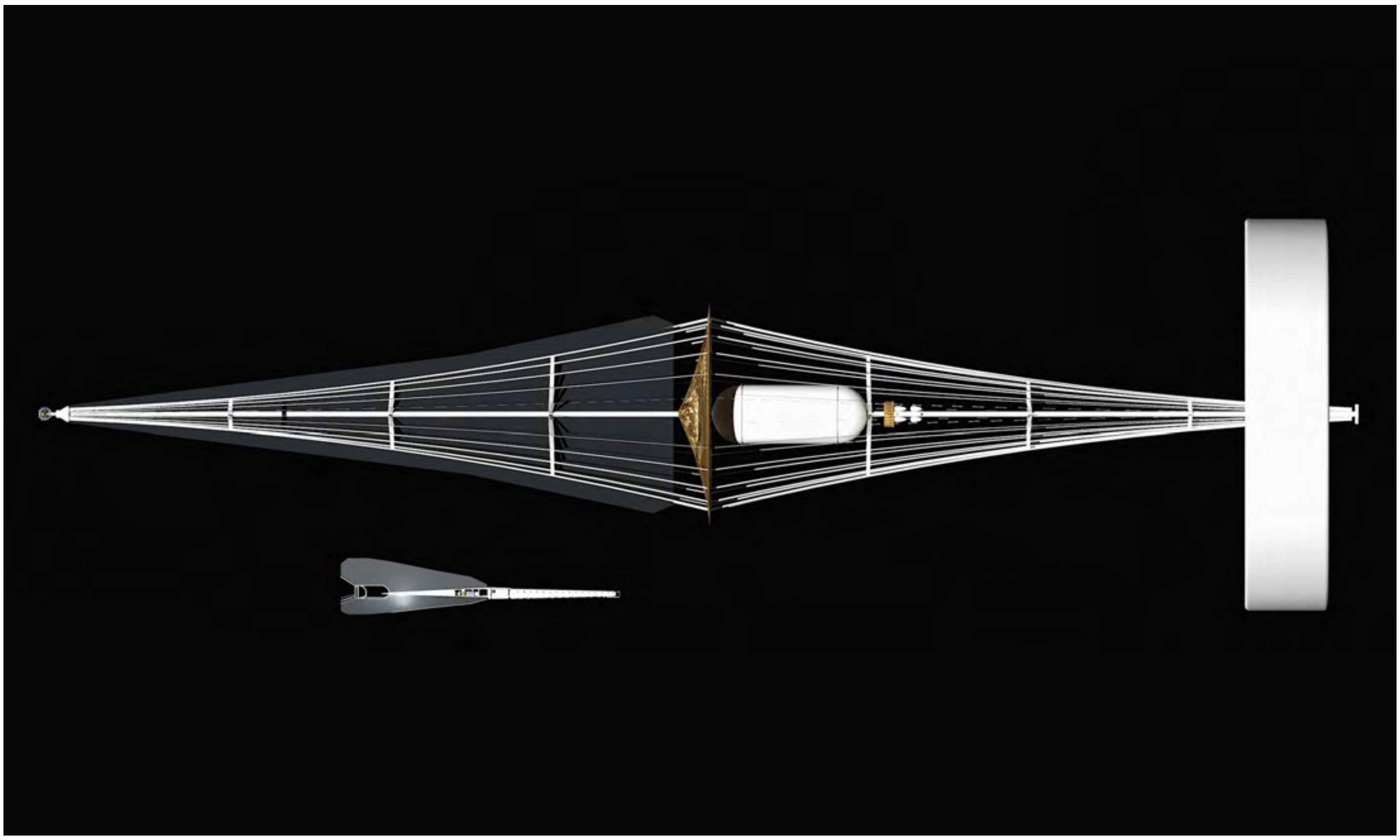

Image 2- Worldship and Firefly*

The Worldship is a large structure, about 4 km in length. The fusion drive occupies one end, while the habitat, a rotating torus 1,200 m in diameter, is at the other end. The radiation shield protects the ship from neutrons escaping from the drive chamber. Radiators dissipate the heat from the radiation shield. Heat from the various drive elements such as the nozzle structure, fusion drivers, magnetic confinement system and shock absorbers is rejected by lower temperature radiators in the same area.

Following the radiators, a multilayer insulation shield protects the habitat and the propellant tanks from the heat emitted by the radiators. The tanks hold liquid deuterium, or a combination of deuterium and helium3, depending on the type of fusion drive used. A technical area follows, housing workshops, the exploration vehicles required to visit eventual planets at destination and to correspond with other vehicles in the Worldship fleet. A large number of self replicating factories, quite analogous to fruits on a branch, lead to the habitat.

* The Icarus Firefly vehicle is an uncrewed probe; the result of the Icarus Firefly study by Robert Freeland and Michel Lamontagne - see next page and *Reaching the Stars in a Century using Fusion Propulsion, A Review Paper based on the 'Firefly Icarus' Design* by Patrick J Mahon in P22, August 2018 - also i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/.

The habitat is composed of two levels: a radiation protected floor with a 5,000 kg/m^2 mineral shield, where the passengers live and sleep, and a large park/biome with much lower radiation protection, where the passengers can experience a more natural setting and look outside the ship. However, the park is a highly maintained area, closer to a botanical garden than a wilderness. The food production and maintenance systems are located on the radiation protected floor. A lightweight, transparent Whipple* shield covers the front of the vehicle.

The main structure of the ship is a hyperboloid tower. The habitat is linked to the tower using cables that are invisible at the scale of the image.

A number of Worldships would travel together. These would probably have variations in design, both for psychological reasons and for protection through diversity.

Icarus Firefly [5][6], shown in image 2 for scale, is a Sprinter type fusion Starship close to the original Daedalus design, but using a different engine configuration. The Worldship torus is similar to, but much smaller than, the original O'Neil Toroidal Space Colony†, itself designed for 10,000 people.

The Worldship proposed here is not a stable structure. However, nothing on the Worldship will be static. The Worldship is a truly dynamic system, that requires constant governance. The problem of maintaining the correct attitude for the Worldship will be trivial compared to the problem of maintaining all the internal systems in operation for centuries. As it is continuously operating, the Worldship cannot break down and coast for centuries, as so often shown in fiction. Its operation is a part of the society's make-up. Rather like a city is part of a society. The illusion of the stable and eternal ecosystem cannot be sustained, just as the neglect of the Earth's ecosystem has shown itself to be non sustainable.

The Interplanetary Society

The constructability of Worldships depends entirely on the capacities of the society that will build them. Although our present planetary society would be incapable of building such a vehicle as it cannot yet build the drive for it or the closed ecological systems required; an Interplanetary Society should acquire the capability. And perhaps acquire it earlier than later in its development. In our Solar System, Martian colonization and Space Settlements, as recently revitalized by Elon Musk in the first case and Jeff Bezos in the second, offer possibly complementary paths forward towards developing the elements required for a Worldship.

Martian colonization

All recent Mars exploration plans [7][8] include the use of In Situ Resource Utilisation (ISRU) to produce propellant and water for the Mars exploration bases and return vehicles. Most early base concepts also include the use of martian regolith to create radiation shielding, and the eventual development of other Martian resources such as Iron/Steel, Glass, plastics and some form of concrete.

The colonization of Mars should be a large scale experiment that will help define the requirements for a workable Worldship. Mars provides an interesting environment, half way between the Earth and a Space Settlement. There is no biome, but there are tremendous energy, water and mineral resources that will serve as stabilisers in the development of life bearing infrastructures for Space. Mars will require compact food production systems, pressurized habitats, high rates of communication and artificial environments that can all later be applied to Worldships. The rate at which Martian regolith can be converted into soil will give the expected growth rate for living soils in space habitats. The isolation of the initial small Martian communities will serve as examples for the isolated communities in the Worldships. The present SpaceX plans[8] call for robotic exploration and preparation of a proof of concept ISRU fuel production plant. This can be seen as a precursor of the work that will be required to build Space Settlements. And as a precursor to the mode of operation of a Worldship as it reaches a new Star system.

* Fred Whipple proposed a multi-layer shield for spacecraft in 1947. Such shields are now widespread in spacecraft engineering practice, see -*Meteorites and space travel* - Whipple, F L, Astronomical Journal, Vol. 52, p. 131, 1947

† The High Frontier: Human Colonies in Space, Gerard K O'Neill, William Morrow and Company 1976. 2001 Edition - Collector's Guide Publishing. Available from bookshop.org

Image 3- An Early Martian settlement. Propellant production on Mars may be a first step in In Situ resources development.

Space settlements

The original O'Neill space colonization[9] paradigm was: Use a space colony (The Stanford Torus) to produce solar power satellites. Finance the construction of the colony with the future revenue from the power satellites. The objective was the occupation of space, the means was power satellites. This could be changed to: Use solar powered self replicating factories to produce affordable Space habitats. Sell the 'land' on the habitat to produce revenue and bring about the occupation of space. Real Estate rather than energy would be the ultimate driver. Affordable Space Habitats require very low costs for transportation and energy. The lowest costs for these come from In Situ resources, most likely from the Moon[9], and low cost energy from power satellites or lunar surface arrays. Space habitats near the Earth, rather than in the asteroids, would benefit hugely from then Earth's resources and industrial base, possibly requiring less technological progress than Mars colonization. However, the development of self replicating factories to reduce costs would certainly help in the development of technologies usable by Worldships, in particular once Space Settlements start reaching out towards the Asteroids for raw materials.

Image 4- A SpaceX Starship docked at an early Space Settlement, Kalpana 2, design by Al Globus(10)

Fusion drives

Space Settlements in the solar system may be interested in moving from their initial construction point to other parts of the solar system. Due to their large mass, this will be practically impossible using chemical or even nuclear propulsion. This might offer an interesting market for the development of large and powerful fusion drives. These fusion 'tugboats' could move from settlement to settlement, providing deltaV on demand. These fusion engines could then naturally evolve into the powerhouses required for Worldships.

Worldship society

A stable society

Worldships are often portrayed in fiction as low energy, stable agrarian societies. However, to accomplish their mission to move from one star to another, a Worldship requires a drive that produces thousands of times the energy a typical habitat requires. For example, our model Worldship requires about 0.3 GW for the habitat, but the drive power is 100,000 GW. Due to the Coulomb barrier in fusion reactions, the energy required to ignite a Starship's fusion drive is a large fraction of the power of the drive itself. Therefore, a fusion Starship must have a power system capable of handling a significant portion of its drive output. For our Worldship, the driver power will be in the order of 10,000 GW. Deriving a small portion of this power to run the habitat ecosystem becomes a trivial exercise, and all inhabitants of a Worldship should have at their disposal a few orders of magnitude more power than any person living on the Earth today. Therefore, it may be best to plan on having a very urban society, with high technological complexity. Since these types of societies are recent we have little experience with their durability, but they do seem more compatible with the available power levels and with the operation of the Worldship. It also seems counterproductive to have a crew of humans spending their time laboring in an agricultural setting while the ship requires attention and supervision.

It is likely that the inhabitants of the Worldships will themselves come from similar space settlements in the Solar system. Living in a space settlement should already be a way of life for the inhabitants of the Worldship. This cancels the founder's dilemma, where the initial enthusiasm that motivated the first generation is lost by the new generation that doesn't necessarily share the initial vision. The Interstellar voyage is then no longer an exceptional and restrictive move, but something akin to business as usual, perhaps with some different circumstances but largely with the same living conditions as before.

The best solution then is to have no founders at all. The operation of the Worldship is a continuation of the operations of the Space Settlements. The only limitation should be some limitations of resources. If these are not perceptible for the length of a trip, then the Worldship society will not feel that it is travelling. Some Space Settlements will already be remote from Earth. When Space Settlements are built in the resource rich asteroid belt, or around Mars, their communication delays will grow to 45 minutes or more. This is enough to create a local community. The Worldship distance will just be a question of degree.

The inhabitants of the Worldship will eventually need to construct a large industrial base at the target star system. As the Worldship itself is an industrial product, it would seem logical for the settlers to be an industrial society, rather than an agrarian society. This favors the inclusions of unfinished elements in the Starships, perhaps even including 'raw' starships in the exploration flotilla, that can be built and modified as the flotilla proceeds towards its target, as proposed by Summerford[11]. This also favors the active participation of the settlers in the maintenance of the Worldships, rather than being mere passengers in an all enveloping technological cocoon.

The lower limit of 3-4,000 people and the use of 'small' Worldships does not mean that the Worldship fleet needs to be that small. The Worldship fleet might be significantly larger, and a larger population would definitively help to stabilize the society by creating more diversity and opportunities. The vision of a mass optimised system operating on a minimum budget may be typical of a governmental agency, and seeing NASA operating for decades in this mode may give the impression that it is the only way. But for a society that has significantly excess production capacities, travelling in style would certainly be the better way to go. In any case, the flotilla concept allows for places to visit. Flotillas set up a large distance away, a few light minutes for example, would replicate the way of life of Space Settlements in the solar system.

The large fleet of smaller ships also answers the problem of the dangerous psychopath, or idiot caretaker. Their reach is necessarily limited. And for those who would like to see the world burn, destroying a single Worldship should be enough of an accomplishment. Staying in contact with the larger domain of Solar system civilisation also means that the problem of the rare genius is solved, up to a point. The genius on Earth can exercise his influence all the way to the Worldship through communications.

Communications vs isolation

The crew of the Worldship, although isolated, will not really be alone. The parent society will have some interest in this distant child, and communications, although slow, will be possible.

Peter Milne [12] has shown that an Interstellar Spacecraft could maintain a 20 gigabits/sec communication with Earth for interstellar distances with a few Megawatts of transmission power. High frequency microwaves in the 20 GHz range with a bandwidth of a few GHz would be sufficient, and laser transmission might offer an even better transmission system. The most enabling technology would be a large transmitter/receiving in the solar system, rather than the system at the Worldship itself. So a Worldship could communicate continuously with the parent world and any other Worldship in a interplanetary convoy. In fact, due to the large mass of the habitat, a Worldship can have a significant mass fraction allocated to secondary systems, and a Worldship could easily dedicate a few GW to a laser sail system capable of driving bidirectional lightsails, such as those defined by Lubin for Project Starshot[13], between the Worldship and the solar system. As Project Starshot aims to create a vehicle moving at 20% of the speed of light, this would allow for the transmission of small quantities of material between the Earth and the Worldship, if needed, while the Worldship was still travelling. Due to the large fuel requirements of a Worldship, it should even be possible to reserve an amount sufficient to refuel a few Sprinter starships such as Firefly, that would require only 22,000 tonnes of propellant out of the more than 26,000,000 tonnes the Worldship would start out with. This would allow delivery of payloads in the 100 tonne range to the Worldship.

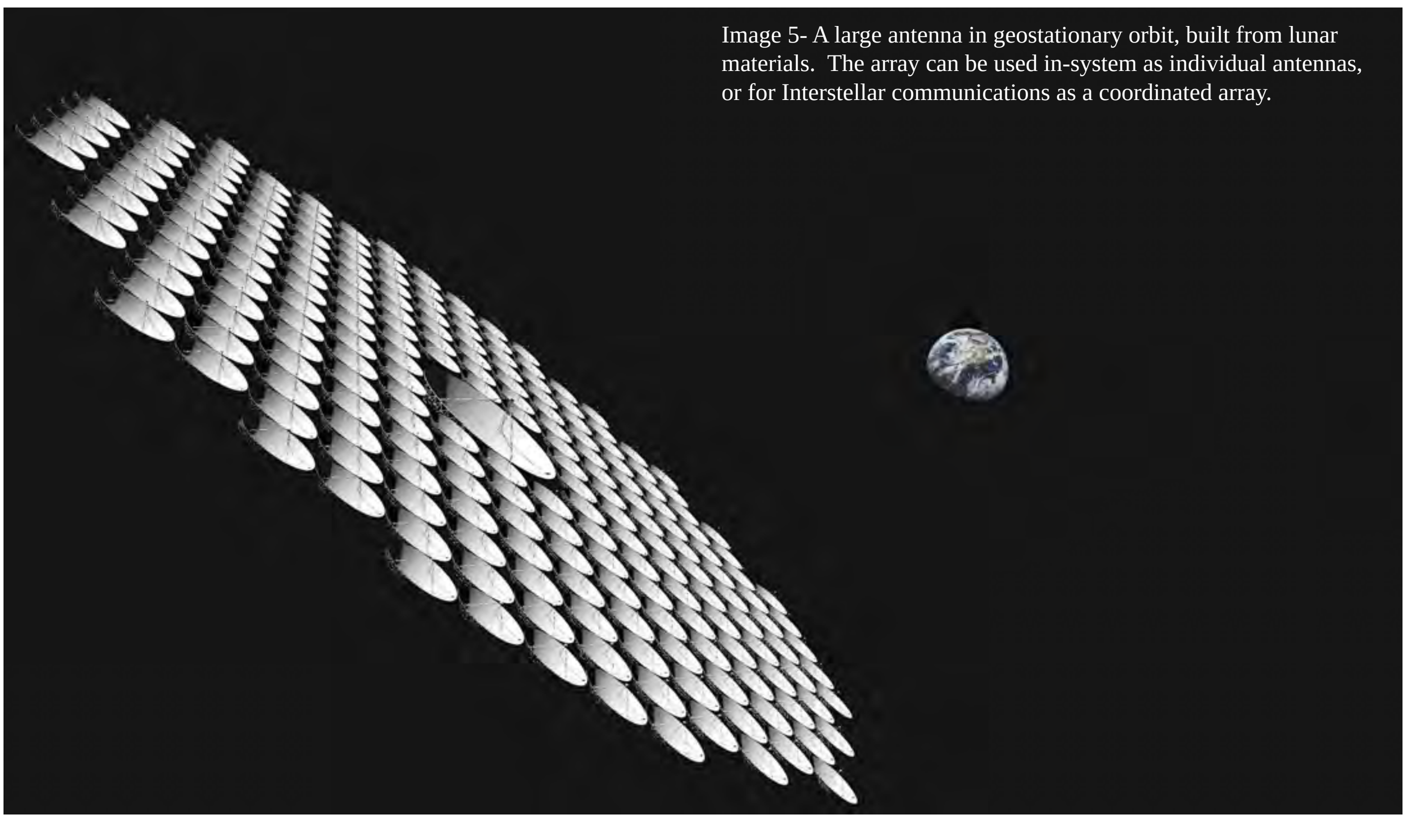

Image 5- A large antenna in geostationary orbit, built from lunar materials. The array can be used in-system as individual antennas, or for Interstellar communications as a coordinated array.

As far as the antenna in the solar system is concerned, large arrays of multiple antennas should be relatively simple to construct, and be in use in the solar system for interplanetary communications long before the first Worldship departs.

Worldship construction

Construction method and costs

The cost of a Worldship to an Interplanetary society seems large at first glance. However, a large part of that cost may be eliminated using the concept of self replicating factories[3]. In particular self replicating factories can produce propellant extraction systems and structural fabrication systems for very low cost with little human intervention, leaving the final small but complex systems, such as the computers and engines,

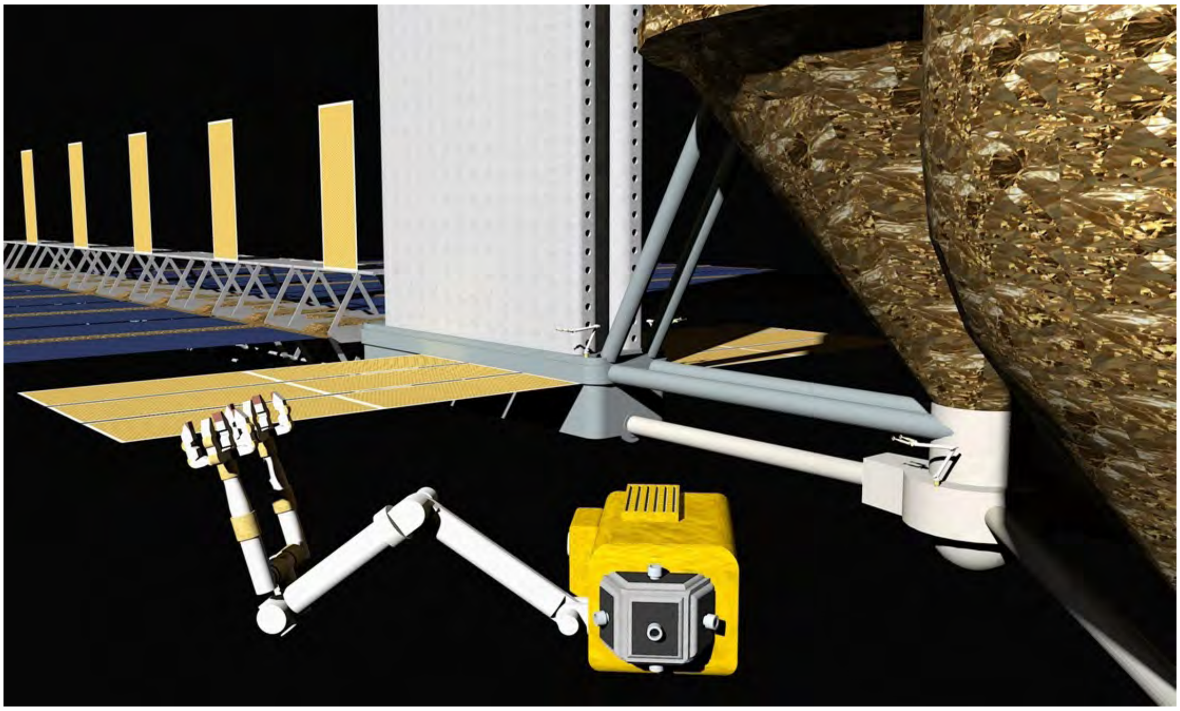

Image 6- A beam maker. Solar power is used to sinter lunar or asteroid regolith into monolithic beams, assembled using post tensioned cables. A small autonomous maintenance robot is in the foreground.

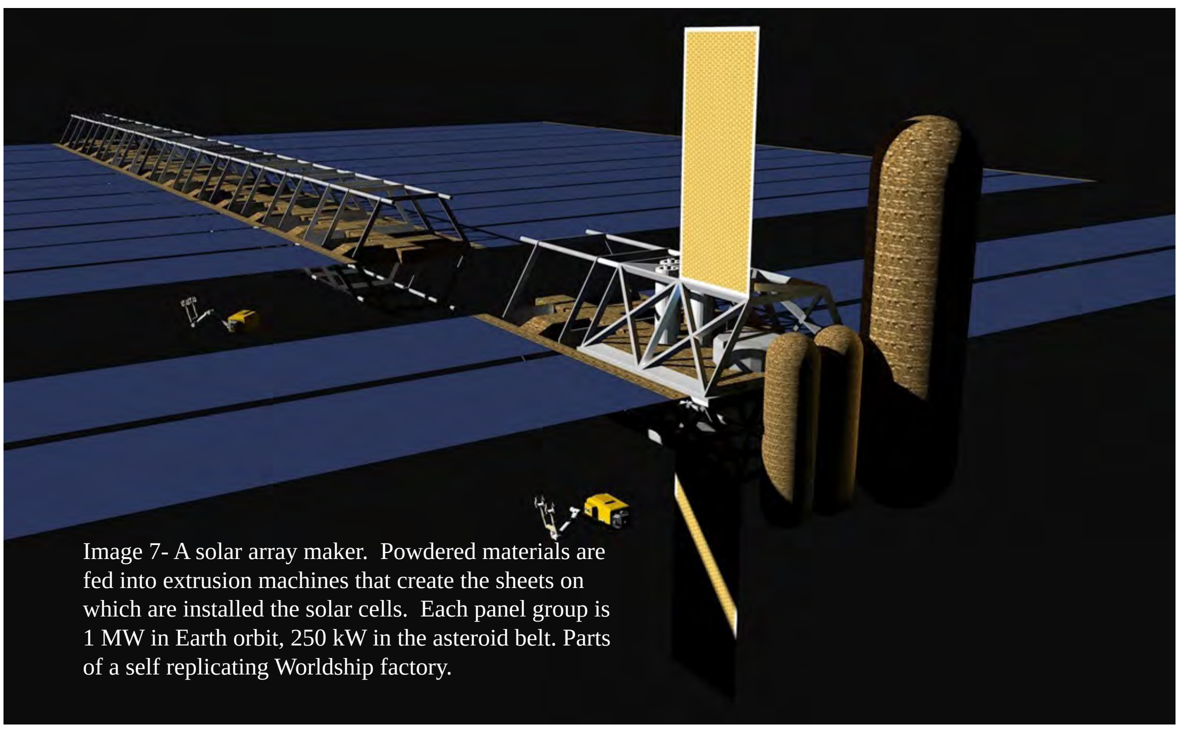

Image 7- A solar array maker. Powdered materials are fed into extrusion machines that create the sheets on which are installed the solar cells. Each panel group is 1 MW in Earth orbit, 250 kW in the asteroid belt. Parts of a self replicating Worldship factory.

to be built by humans. Totally or partially self replicating machines would allow humanity to use a larger fraction of the solar energy output without necessarily increasing the size of the economy to match the available energy increase. The same way humanity already uses the energy embodied by self replicating plants for their growth, without actually controlling or paying for that energy in the economic system.

The two main parts of a Worldship are the habitat and the drive. Most of the habitat is ‘simple’’ mass: radiation shielding (probably some form of sintered regolith or concrete), structural elements (Aluminium, steel or composites), an internal atmosphere, water and soil. This particular worldship design also has a large amount of glass for the park. A very small part of the overall habitat mass is more complex materials, such as living organisms, lighting and controls of life supports systems and food production systems.

The drive part is more complex and high maintenance, with high temperature materials, computers, workshops and the fusion engine itself. The radiation shield, by far the largest part of the mass of the Worldship, requires no maintenance at all.

Most of the mass of the Worldship also has low embodied energy. While concrete has an embodied energy of about 1 MJ/kg and steel is in the order of 30 MJ/kg[14], the energy in computer equipment and other complex systems is more in the order of 4000-7000 MJ/kg. Using low embodied energy materials reduces the cost of the Worldship considerably. The complex, sophisticated part of the Worldship may be in the order of one hundred thousand tonnes of the approximately twelve million tonnes vehicle, perhaps one thousands of the mass. So only that small portion of the Worldship is expensive to build. The rest of the Worldship should be rather cheap.

Energy and material costs

The ecosystem of the Earth has stored over millions of years tremendous amounts of solar energy in the form of gas, oil and coal. And every year stores huge amounts of energy in plants and trees. To the point that that energy seems free. In the same way, solar powered factories can produce and store energy in elements such as mineral beams, metallic structures and propellant depots that can be used to build Worldships or space settlements. The energy costs for extracting and using fossil fuels or natural materials are generally the only one accounted for in the operations of a society. An interplanetary Society might act in the same way, using prepared resources but, in a sense, not paying for them, as they would be the results of a production environment that supplies them without requiring payment in any form.

Maintenance

The Worldships will be complex systems, with numerous parts and subsystems. For a small crew of a few thousand, even when trained in technology, most maintenance will need to be automated, carried out by robotic equipment or self healing systems. Ecological systems will also require maintenance, and although this might be seen as a kind of farming, the small size of the community might mean that no more than a dozen people would be actively involved in agriculture.

Maintenance on the worldship would also be helped by the presence of at least one large self replicating factory, that by definition will be able to carry out any number of complex construction, and by extension repair, operations. However, the presence of a human crew reduces significantly the artificial intelligence required by the factory, reducing it from the level of a quasi self aware ‘agent’ to a rather more accessible level of semi autonomous operations.

On a Worldship there will be no externalities, except for the tremendous amount of power available from the drive. Although a materially closed system, the Worldship habitat has much more energy available than the original Earth habitat. And although missing the tremendous material reservoir that a planet represents, the Worldship should be able to make up this absence by the availability of an equally large energy supply. The Worldship will also benefit from the information storage capabilities of computer systems. Every single element of the Worldship, every component, part or system will be completely described in the Worldship’s data banks, and include the entire procedure required to fabricate it. And the Worldship will carry the equipment necessary to carry out that task. The only exception will be the biological systems, whose complexity will still be greater than the complexity of the machine carrying them. Over the centuries of travel, it is likely that most of the working elements of the ship will need to be replaced. Rather like the ship of Theseus, but one that will draw most of its new components from the old ones, rather than from the environment.

Recycling

As it has no access to external material resources, the Worldship will need to recycle everything. As the Earth already does with its many cycles: water, oxygen, nitrogen, calcium and carbon. Beyond standard systems already used on Earth or the ISS, the large amounts of energy available on the Worldship can be used to break down complex debris into its component atoms using high temperature and plasma furnaces. The individuals elements can then be separated. The limited time required for the trip may also allow for the storage of some primary materials, such as Rare Earths. Using as a basis of reference the average use of under 1 kg per person per year today on Earth, the Worldship could start out with 500 tonnes of Rare Earth storage and survive on 500 years with that stockpile. On a similar basis, with the worldwide production of platinum at about 200 tonnes per year, the Worldship could set out with 100 kg of platinum and never be expected to have to recycle any of it.

The Worldship itself will need to have recycling build into its design, rather as modern electronic equipment and vehicles are starting to have. And the Worldship biosphere will also do its part in recycling, with the possibility of non biological support if the equilibrium is lost.

With losses inevitable in any system, the Worldship should start its trip with reserves of critical material. The CHON (Carbon, Hydrogen, Oxygen and Nitrogen) elements are likely the most critical. Water in particular is a critical resource, and it might be good to replace some of the radiation shield with a water shield.

Resource extraction

Although there are no resources available in deep space, a Worldship will require resource extraction systems at both the beginning and the end of its voyage. A Worldship with in situ resources extraction systems will also have extensive exploration capabilities. These will be adjusted depending on the discoveries made at the target Star system. After all, the Worldship is not only a mode of travel, it is a habitat that would be expected to be lived in and change, both before and after the arrival at the target star system. And although the Worldship is somewhat like a seed during its travel time, the culture it transports will want to flower, just like any living organism, when it reaches a place that allows for growth by providing resources. As the development of an Interstellar Society that is capable of producing a Worldship requires in-situ robotic production techniques to develop, these will be available for the Worldship itself. The most important ones being the means of extracting large volume items such as gases, liquids and primary metals and minerals.

Although a Worldship is a large machine, it must be remembered that at 11 million tonnes, mostly built from a material that is very close to concrete, it is only twice the mass of, for example, the Daniel-Johnson hydroelectric dam[15]. That was built using a small part of the resources of a relatively small nation in the 1960s.

Daniel-Johnson Dam and Manic-5 Generating Station

Credit: hydroquebec.com

Self replicating factories

The concept of self replicating factories can be worked into the concept of Worldships and into the concept of a future solar system wide economy.

What is the difference between a self replicating factory and people, that are also self replicating? First, the length of a generation should be significantly shorter: Most complex projects in construction today are done in about two years. This is an order of magnitude less than the time required per human generation. Machines also have much simpler power systems, with electricity being able to power equipment directly, rather than the more complex system of growing food and eating used by humans. Machines can survive in vacuum, while humans can't. And of course humans are infinitely more flexible than machines, being able to run a kilometre, knit a sweater or write a poem, while self replicating machines are limited to a very specific number of tasks. Also, humans are fully self replicating, while it is likely that for a long time self replicating factories will have some number of externally provided parts. In a sense, these parts will act like a growth limiter, or vitamins[2], with the absence of the part making the completion of the machine impossible. A self replicating factory is much closer to a tree than to a human.

The self replicating factories would be used to create the simple, but massive, parts of the Worldship. The main elements ranked by mass would be:

- Deuterium (and He-3) propellant
- Regolith beams for radiation protection and basic habitat structure
- Steel/carbon fibre cables for the hoop and pressure stresses in the rotating habitat
- Glass elements for the habitat
- Sand and clays for the soil of the habitat
- Water for the habitat
- Structural extrusions for the tower structure
- Nitrogen for the habitat atmosphere
- Oxygen for the habitat atmosphere
- Hydrocarbon sealants
- Extruded sheets for tanks, radiators and radiation shields

Computers, controls, power systems, organisms for the soil, farms and the crew would probably come from Earth or from existing space settlements.

The degree of self replication is critical in the design of the mission. If fully self replicating systems exist at the departure of the mission, Sprinter starships carrying self replicating machines can be sent at the same time as the Worldship flotilla departs. The Sprinters will arrive centuries before the Worldships, and the self replicating machines will have ample time to create multiple habitats, and perhaps begin to seed them with simple life forms. In fact, the self replicating machines should be able to build habitats faster than the human populations is likely to expand. So the paradox of the fast Sprinter ships versus the slow Worldships can be avoided; it doesn't matter if later ships are faster than the Worldships, the factories can build enough space for all*.

Image 8- A Worldship and large sprinter ship with the same basic design. As most of the mass of the Worldship is in the habitat, removing it, while keeping everything else identical, allows the sprinter to arrive at the target star in ¼ of the time the Worldship requires. It could then use self replicating factories to build habitats into which the Worldship population could expand on arrival.

* en.wikipedia.org/wiki/Interstellar_travel#Wait_calculation

Factory arrangement

The elements required for a self replicating factory are described by Hein[2] and others.

- Resource extraction and refining
- Chemical processing
- Casting, sheet metal rolling and extrusion molding
- Additive manufacturing
- Conventional tooling
- CAD-CAM-AI
- Semi autonomous robots

If a factory is able to produce 100 solar units per year, after 20 years it will have produced 2,000 solar units.

With exponential growth: x(t)=x(0)*2(t/T) where t is the time, T is the doubling time and x is the initial number of factories. If it takes 2 years to build a factory, after 19 years one factory will have produced 1*2(20/2)=512 factories. If these then turn to produce solar panels, they will build 51,200 solar units in the following year.

Some of the elements required for the self replicating factory may not be easily available at the target star system and it might be necessary to use supplies brought from Earth for closure. Rare Earths metals, nuclear materials and generally any materials in low concentrations may be hard to process in reasonable times.

Although additive manufacturing is very flexible, it is also quite slow. Conventional extrusion and casting will be advantageous for large structural items of sheet metal parts and would be included in the factory.

The self replicating factory can also adjust its configuration and in particular modify its mineral processing facilities depending on what is found at the target solar system. The supplies brought from Earth can be arranged into the required configuration as observed in situ. For example, free flying ice crushing equipment for small (km sized) icy moons, or rovers and more substantial diggers for larger rocky moons.

The factory would be used to build other specialised factories, such as solar cell makers and regolith beam makers. It would only duplicate itself if the rate of progress using a single factory was too slow.

A common objection to the self replicating factory idea is that the production chain is too complex. An example often used is the production of microprocessors and the cost of microprocessor plants, or Fabs, that is ever increasing and reaches billions of dollars. The recent development of the minimal Fab technology[16], that allows for small runs of complex microprocessors is a solution to that problem that should be applicable to self replicating factories.

The most important chain that is needed is probably the steel production one. Steel castings lead to metal machine tools that can produce precise elements for further fabrication. Iron ore reduction methods using methane rather than coal would allow for steel production wherever water and CO_2 can be found in the solar system.

It is important to note that the self replicating machines described here do not create themselves Ex nihilo. They require an existing self replicating machine that can already provide the array of precision tools required to build and maintain the new precision tools, and a tremendous store of knowledge in its computers. In a sense, the self replicating factory is the smallest unit of the self perpetuating technological society that is possible.

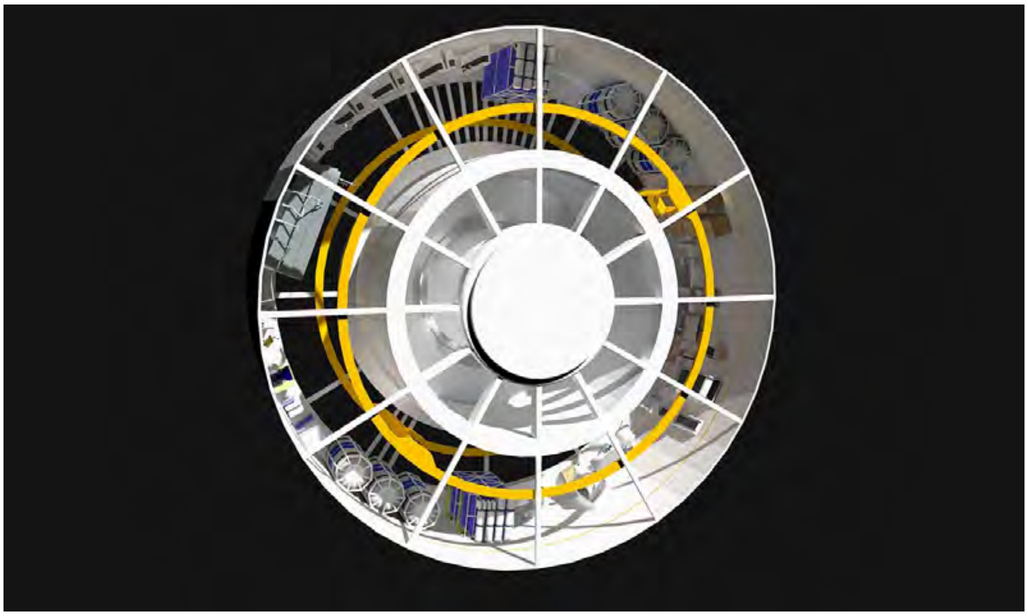

Image 9 - A self replicating factory, showing the production section. A half completed beam maker (see image 6) is shown at left.

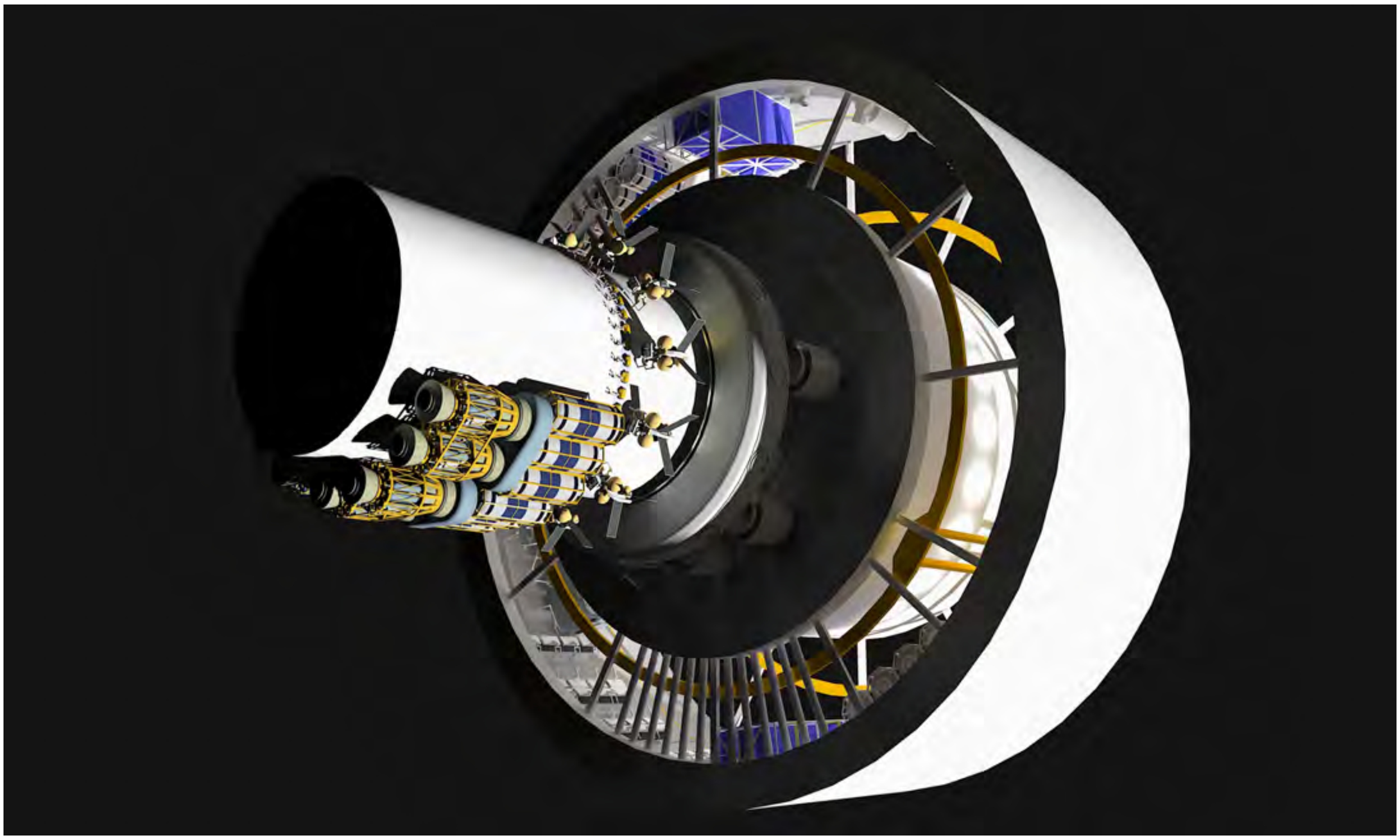

Image 10- Another view, showing the resource extraction equipment built for operations on a small ice moon or asteroid

Worldship Ecology

Building a sustainable ecology

The small size of the habitats that result from the populations proposed by Hein & all are unlikely to be able to sustain stable ecologies. The entire living area of the Worldship is just above 1.6 km², while the habitat required for a single apex predator, such as a Siberian tiger, is over 1,000 km². The upper layer of soil and water ultimately required to support the tiger's ecosystem would mass from 300 to 1,000 times more than the mass of the Worldship. However, the Worldship doesn't need to have a truly sustainable ecology, it just needs to have an ecology that can survive until a sufficiently large habitat can be recreated at the target star system. And these habitats do not need to be filled with humans. It is entirely possible to produce space habitats that serve only a local ecology. The human population can grow much more slowly than the livable space available. And the Worldships can carry all the information required for much larger ecological systems than those they themselves can sustain. They will probably need to carry frozen samples of the larger animals that the small Worldship ecologies will not be able to support.

In the solar system, the Earth will provide a stable ecological reservoir to act as a backup for the space settlements. In the new settlements around other star systems, if there are no habitable planets to serve as ecological reservoirs, it will be the task of the settlers to create sufficient space to provide these reservoirs. These will probably take the form of the larger types of space habitats, or of swarms of smaller ones.

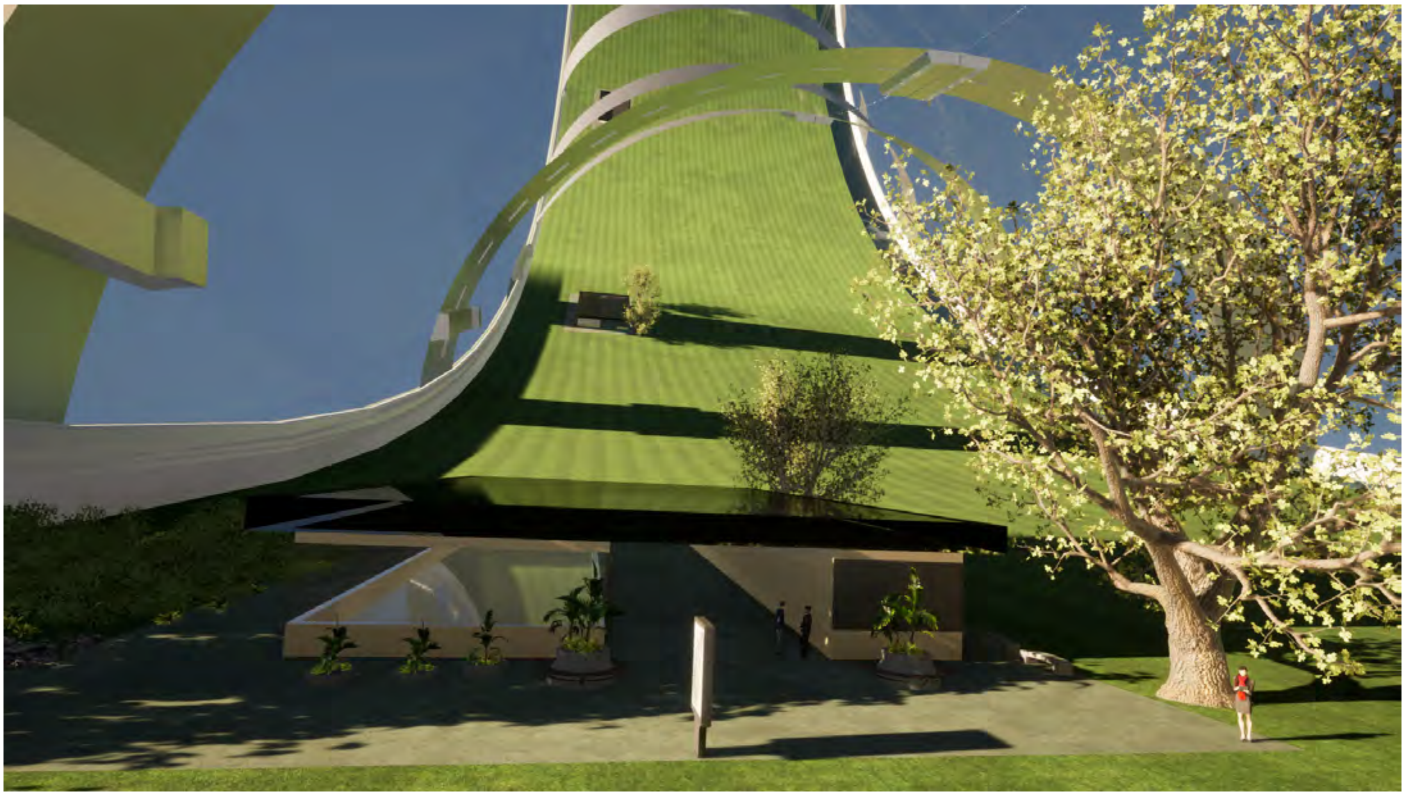

Image 11 - Interior of the Worldship forest habitat

It is also important to note than once a star system is reached new ships will continue to come along from Earth, to enrich the ecology and help create the larger system required for stable life.

In the 2015 TVIW paper by Cobbs [17], three separate biomes were suggested: Ocean, Grassland and Temperate forest, to provide maximum diversity. These could be implemented in three different Worldships. These would not be used as food sources to support the human population, as they would be much too small, rather they would serve as biological reservoirs to provide a base population to populate space habitats built at destination. The well known failure of Biosphere 2, with just over one hectare of area, sets a lower size for an independent biome. By necessity, space settlements in the solar System will have served as base design to test the stability of small ecosystems before the Worldships set out, and that the 240+ hectares proposed here for the Worldship flotilla will have been proven to be sufficient.

The energy required for an ecology on Earth is simply the solar constant, divided by the night and day cycle and with some losses from the planet's albedo. This is approximately 300 W/m² (1,300 W/m² divided by two for night and day and again by two for the spherical form of the Earth, plus some losses here and there). So a space Settlement, or a Worldship, simply needs to provide 300 W/m² of light to any surface capable of sustaining life, with gravity, air, water and soil plus a number of trace elements. Life will take care of the rest.

And to provide a self sustaining ecology at the target system, rather than depending on the presence of an habitable planet, with all the dangers and problems that terraforming may present, it seems likely that the Worldship will carry a number of the self sustaining technologies that helped build it, as well as some of the more sophisticated elements required for the construction of the space settlements. In fact that may be the true defining factor for the size of Worldships: At the target systems, these need to provide the technological basis and the intellectual capacity required to create new space settlements.

Discussion

The very existence of Worldships or of an Interplanetary society may well depend on the nature of an eventual technological singularity, that might render moot the whole idea in Interstellar Travel, or otherwise create opportunities that cannot be envisioned today other than by Science Fiction.

At the scale of an Interplanetary Society, Worldships should be tiny objects.

Self replication and AI may be much harder than expected.

The ecological system may self destruct through instability, destroying the main value of the Worldship concept.

It may be impossible to maintain a technological society over five centuries.

The three generation paradigm, also know as from Shirtsleeves to shirtsleeves in three generations*, or the founder's dilemma, may all make the long term survival of a Worldship impossible.

Althought the ships described in this essay are fusion powered, Antimatter powered ships might provide an interesting alternative. Antimatter is not an energy source, it is simply the ultimate battery. But in a solar system where self replicating factories can produce solar power satellites in tremendous amounts, manufacturing the antimatter using that solar power should be possible.

Conclusion

Using methods developed for the exploration and occupation of the Solar System, notably self replicating factories, it should be possible to build Worldships for a small part of the budget of an Interplanetary Society. By increasing the available energy and resources beyond the usually understood bounds of the economy using self replicating factories, Worldship might be less expensive than expected. The main analogy being that a mechanical 'ecosystem' would provide external resources that could be used at a cost that excluded most of the energy and material required to generate these resources, the same way Earth societies still use plants and trees from the planetary ecosystem without accounting for the work of the ecosystem to create these resources.

Image-12 Worldship habitat, looking down towards the engine radiator thermal shield and the fuel tank.

* Editor's Note: Known as "rags to rags in three generations" during my childhood in industrial Lancashire. eg Braithwaite worked hard and created Braithwaite and Son, his son had it cushy and thought his own son should become a "gentleman". Instead he become a waster.

References

1. Hein, Andreas M., Smith, Cameron, Marin, Fréedéric, et al. World ships: Feasibility and Rationale. arXiv preprint arXiv:2005.04100, 2020. arxiv.org/abs/2005.04100

2. Hein, Andreas M., Pak, Mikhail, Putz, Daniel, et al. World ships—architectures & feasibility revisited. Journal of the British Interplanetary Society (JBIS), 2012, vol. 65, no 4, p. 119.

3. Hein, Andreas M. et Baxter, Stephen. Artificial Intelligence for Interstellar Travel. arXiv preprint arXiv:1811.06526, 2018. arxiv.org/abs/1811.06526

4. Borgue, Olivia et Hein, Andreas M. Near-Term Self-replicating Probes--A Concept Design. arXiv preprint arXiv:2005.12303, 2020. arxiv.org/abs/2005.12303

5. Mahon, Patrick J. Reaching the Stars in a Century using Fusion Propulsion. i4is.org/reaching-the-stars-in-a-century-using-fusion-propulsion/

6. Freeland, R. M. Plasma Dynamics in Firefly's Z-pinch Fusion Engine. JBIS, 2018, vol. 71, p. 288-293.

7. Drake, Bret G., Hoffman, Stephen J., et Beaty, David W. Human exploration of Mars, design reference architecture 5.0. In : 2010 IEEE Aerospace Conference. IEEE, 2010. p. 1-24. (slides: ntrs.nasa.gov/api/citations/20090012109/downloads/20090012109.pdf)

8. Making Life Multiplanetary www.spacex.com/media/making_life_multiplanetary_transcript_2017.pdf

9. O'Neill, Gerard K., et al. The High Frontier: Human Colonies in Space. 1977.

10. Globus, Al, Covey, Stephen, et Faber, Daniel. Space settlement: an easier way. NSS Space Settlement Journal, 2017, no 2. space.nss.org/wp-content/uploads/NSS-JOURNAL-Space-Settlement-An-Easier-Way.pdf

11. Summerford, Steve, Colonized Interstellar Vessel: Conceptual Master Planning, Project Hyperion design study, 2012 www.icarusinterstellar.org/colonized-interstellar-vessel-conceptual-master-planning

12. Milne, P., Lamontagne M, Freeland R - Project Icarus: Communications data link designs between Icarus and Earth and between Icarus Spacecraft. JBIS, 2016, vol. 69, p. 278-288.

13. Lubin, Philip. A roadmap to interstellar flight. arXiv preprint arXiv:1604.01356, 2016. arxiv.org/abs/1604.01356

14. G.P. Hammond and C.I. Jones (2006) Embodied energy and carbon footprint database, Department of Mechanical Engineering, University of Bath, United Kingdom circularecology.com/embodied-carbon-footprint-database.html

15. en.wikipedia.org/wiki/Daniel-Johnson_dam

16. ww2.frost.com/frost-perspectives/minimal-fab-technology/

17. Cobbs, C. C., et al. Ecological Engineering Considerations for ISU's Worldship Project. JBIS, 2015, vol. 68, p. 81-85.

About the Author

Michel Lamontagne is one of the two principal developers, with Robert Freeland, of the Firefly interstellar probe design for Project Icarus. Michel is a French Canadian living near Montreal. He works as a mechanical engineer, mainly in building systems: plumbing and HVAC. He's been a member of Icarus Interstellar for five years, mostly working on the Firefly study. As you will see from the illustrations here, and his cover are for P22, P30 and P31, Michel is an artist as well as an engineer. He mostly worked in comic art in his earlier years; you can find examples of this earlier work (up till 2014) on the web site: sites.google.com/site/bdespace/Home - use the side menu for most images. His more recent work is on Deviant Art: www. deviantart.com/michel-lamontagne/gallery/.