WR 327

Interplanetary Supply Chain

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An analysis of current and developing technologies to be used in an interplanetary supply chain system.

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Abstract

Several new technologies in development will enable us to expand our civilization into the solar system, not only for the sakes of exploration and adventure, but also for the cultural and economic growth of our species. This report attempts to create a top down view of the major components of any future supply chain system that would be implemented to make this feasible, by examining certain activities and developments by government and business entities such as NASA, SpaceX and Planetary Resources. An advanced interplanetary communications system will be another necessary development for sending messages beyond the earth-moon system. The most likely solution would be a directed laser relay system utilizing the earth-sun Lagrange 4 and 5 points to open access to Mars and the outer solar system. An increase in the production of satellites will be essential in making this communication network possible. Installing these communication networks will provide the information sharing required to make an interplanetary supply chain possible. Advancements in space habitats are another necessity also critical to creating livable conditions in space and on colonizable planets. These advancements include artificial ecosystems and medical advancements to respond to new conditions produced by living in space such as radiation exposure. SpaceX is making significant strides in reducing the costs to launch a rocket into space with the Falcon 9, which will be capable of multiple take offs, thus lowering the price of commercial space flight for commercial and personal use. Other technologies such as the SABRE engine by Reaction Engines may also push interplanetary supply chain forward by developing engines for spacecraft with single-stage-to-orbit capabilities, creating opportunities for an increase in interplanetary travel and reduced resource costs. Planetary Resources and Deep Space Industries are advancing satellite technology with the explicit goal of mining asteroids for rare metals and water. Mining asteroids for precious metals has a high potential for commercial success and could radically transform the entire human economic system, while rendering obsolete environmentally harmful mining and industrial activities on earth soil. With so many avenues of opportunity opening, more and more businesses and individuals should be considering the possibilities of expanding into space.

Introduction

Objective

To develop a working model of what technologies and resources will be necessary to build a general interplanetary supply chain system to be used to develop a space economy.

Context

When the United States' NASA program succeeded in putting man on the moon in 1969, it was the beginning of a new era for all of mankind. Or so we would have thought, based on the famous words of Neil Armstrong, "One small step for a man, one giant leap for mankind!" Americans, and humans around the world imagined that civilization was right on the brink of expanding into the stars.

Yet things have clearly progressed differently. Not only has human civilization never colonized another planet, but space programs have had severe reductions in funding for operations and research, resulting in a perceivably failed space program upon the second explosion of one of the United States' space shuttles and the program's subsequent reliance on rented seat space on Soviet era rockets. Gone was the promise of an advanced human civilization expanding out into the galaxy.

Within the past couple of years, there has been a significant shift in the entire paradigm. The responsibility of advancing aerospace systems to further enable the exploration and colonization of space is no longer solely held by government bodies. With the advent of the SpaceX Falcon 9, Blue Origin New Shepherd, and other new, innovative, reusable rockets from the more competitive private industry, that is finally beginning to change.

With the advent of reusable space rockets, it is finally time to take into serious consideration what it will look like for human civilizations to begin colonizing other planets. While NASA and certain interested companies may take the lead in establishing bases on the moon and Mars soon, an infrastructure needs to be built to accommodate human settlements, transportation of resources and sustained lines of communication between the new outposts of humanity.

Resources

To date, no comprehensive study has yet been performed (and released to the public) which considers these newly developed technologies to plan an infrastructure that could be used to facilitate colonization of the rest of the solar system. However, there was an MIT study which concluded in 2011 that focused on a supply chain model for space exploration purposes. This report attempts to build on the foundations provided by that study, but with an emphasis on using technologies currently in production to build a substantial space economy.

Scope and Limitations

For any sort of economy to be developed because of space exploration, such an infrastructure will be critical to have in place. This paper will discuss the integration of a variety of technologies either currently being used or developed today, and how they will contribute to the larger system. Due to the scale and scope of this study, a very broad overview will be given, while getting into few of the minor details. For example, beyond building a space port on the Moon or Mars, ground based infrastructure will not be considered. Not because they would not be relevant to developing a space economy. But because for the purposes of this paper, they are considered to be separate systems which would also require a comprehensive study.

Terrestrial Supply Chain Models

Supply chain is a system which takes raw goods and materials to be processed, manufactured and then distributed to customers. Supply chain systems are composed of physical distribution channels such as freight or rail lines transporting goods from a materials supplier, to a manufacturing center, to the customer; and information sharing channels, which would include networking channels such as telephone lines and internet/intranet systems.

An MIT study which concluded in 2011, called the MIT Space Logistics Project, outlined several models on which to base a new interplanetary supply chain model in the interest of supporting space exploration. At the time, there was no interplanetary exploration logistics model suitable for actual space-based exploration. Called the Interplanetary Supply Chain Management and Logistics Architectures (IPSCM&LA) Project, the study outlines the following "Classes of Supply", or COS, as possible models to study:

- The NASA/Space Agency model
- Military Logistics models
- Business supply chain models

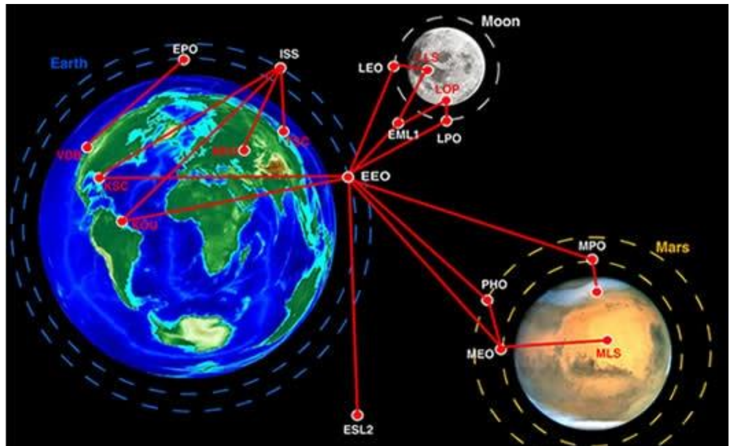


Image 1. Credit: MIT Space Logistics Project

I will examine each of these models briefly in this report, and propose which elements of each to incorporate into a new model which would not only support space exploration, but human colonization efforts and a framework on which a supply chain an ultimately a dynamic economic system may one day thrive.

The NASA Model

The space agency model as developed by NASA relies on a few specialized businesses and NASA facilities to develop space vehicles and other space technologies for primarily exploratory purposes. An overview of the Goddard Space Flight Center's supply chain management functions is shown above. This has been the main mode of civilian space-based activities since the 1960's, and will remain so into the near future.

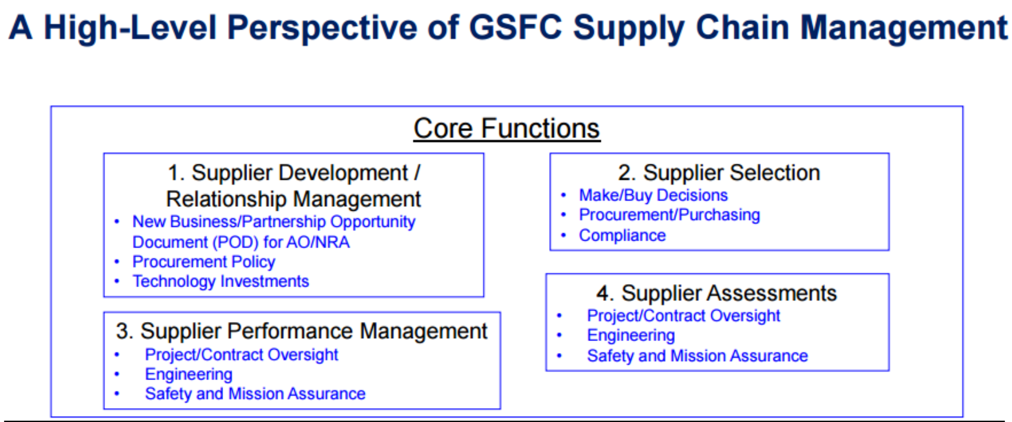


Figure 1: The Core Functions of Supply Chain Management at the Goddard Space Flight Center

The main benefit of the NASA model is that it uses specialized businesses and research groups to accomplish technological challenges and to gather new information about space and planetary environments. However, because of shifting government directives with each new presidential term, NASA and other space programs face constant budgetary constraints. The main drawback to this model is that it is highly expensive and risk averse because each piece of equipment is prohibitively expensive and time consuming to build. When these factors are paired to issues of government financing, this model becomes inadequate for goals beyond initial space exploration.

Military Logistics

The MIT study also highlights military logistical models used by the United States military and NATO. In its 2012 Logistics Handbook, NATO defines its logistics services to be subdivided into the three "domains" of production logistics, in-service logistics, and consumer (or operations) logistics. Each of these covers the following areas:

Image 2: Personnel Transport
Credit: NATO.int

- design and development, acquisition, storage, transport, distribution, maintenance, evacuation and disposal of materiel;
- transport of personnel;
- acquisition, construction, maintenance, operation and disposition of facilities;
- acquisition of provision of services;

- medical and health service support. (NATO Logistics Handbook)

Because of the initial challenges of establishing human habitats in space or on other planets with few or no resources, a military style model could be used to address some of the initial logistical challenges that early human settlements would face.

In wartime, military bases can face sustained periods of limited or even no access to necessary supplies. In response to this challenge, militaries have developed strategies to address issues of limited supply and maintenance over long periods of time. These strategies include system redundancies, backup supplies and emergency transportation systems.

Established space colonies and planetary bases will, at least initially, need to utilize these and other military outpost strategies by using back-up systems and large caches of supplies that cannot be produced in-situ. The primary challenge will be emergency transportation systems, which will need to come fully stocked with all the systems necessary to maintain human survival while in transit back to earth or the nearest space station for help. This is where the military model will shine, because these are exactly the challenges that have already been addressed to some degree in plans regarding submarine or long-term flight mission safety. Some modifications will need to be made to address the specific challenges of human safety in space flight, but it makes an excellent starting point.

The primary limitation of the military model is that it is very expensive to maintain. This model requires huge stores of inventory and large investments in technologies and failsafe's. While it would be the most effective initial progression from the exploratory model that NASA uses, additional considerations must be made for the establishment of a full space economy.

The Business Model

Business supply chain models are among the best well-known, but they will have limited application until certain systems are in place. Once space and planetary settlements have been established with a system of governance with reliable transportation systems, then commerce will be a going concern for the people living in that settlement. Many of the settler's primary needs will be taken care of by 3D printing and other resource utilization technologies to enable the building of structures and expansion of systems in these bases. While farming efforts will be made, at least in the near term, the earth will remain a primary food source at least until each settlement grows to a point of relative self-reliance and food stability.

Image 3: Supply Chain Management
Credit: LinkedIn

The main limitation of the business model is that it needs a market to be implemented in. That means that either it needs to be built on top of an existing model, or the groundwork for an entire market system will need to be established at once.

A New Model

A new model which utilizes aspects of each of the previously listed model would be the best tool to use to build a new space-based infrastructure. Space is an incredibly expansive place, even just within the confines of the local solar system. This means that there will always be an exploratory aspect to living in space. Once a place has been explored, then outposts can be established which utilize the redundancies and stockpiles favored by military models as needed, but which also will have framework put in place to improve the settler's way of life by enabling trade. In the next part of this paper, current technologies and methods will be considered that can make this new system possible.

Technologies Considered

Transportation

The biggest obstacle that prevented human civilization from creating a large and sustained presence in other parts of the solar system has been the difficulty of sending people and equipment off the earth's surface in the first place. There are many transportation methods and types of engines that can be used once in microgravity, but here we will focus on the most critical methods to getting out of the earth's gravity well.

Reusable Rockets

The United States space program, now called NASA, was originally formed as a spin-off of the Air Force as a response to Russia's own space program during the Cold War. While both nations could rise to the challenge of not just sending rockets to space, but humans as well, they soon realized that it was a very expensive endeavor. This is because of what is known as Tsiolkovsky's Rocket Equation:

Image 4: SpaceX Falcon 9 Credit: SpaceX

$$\Delta V = V_e \ln(M_o/M_f)$$

The equation tells us that to get out of the earth's gravity well, for each bit of mass to be taken up (including the mass of fuel) a significant amount of thrust is needed. This has presented a huge challenge in rocketry, because it makes rockets very expensive to use. Rockets are very expensive to build, but are essentially large fuel tanks with a controlled, highly focused and directed explosion that makes them work. Traditionally, each rocket was discarded after use, which only contributed more to how expensive it was to send people and equipment into space.

As of two years ago, reusable rockets are being regularly flown by companies like SpaceX and Blue Origin to take NASA payloads to the International Space Station. Just since SpaceX began flying its rockets in

2008, it has brought down the cost of flying to low earth orbit from $450 million per mission when the space shuttle program was retired in 2011 down to $62 million as of March 2017 (Jackie Wattles, CNNtech). Elon Musk, the founder of SpaceX has disclosed that he hopes to reduce the cost of launch by an additional 30% in the near term (Times of Oman).

To date, SpaceX is the only company to have flown a reused rocket to the space station, and as of the writing of this paper may be one day from also become the first to reuse a space capsule capable of transporting human beings. Blue Origin, founded by Jeff Bezos and located in Kent, Washington, has also successfully landed and reused rockets, but not yet ones that can reach the ISS. Blue Origin's New Glenn orbital rocket, which is currently in development and slated for its first test launch in 2020 (Spacenews) will present be a direct competition to the SpaceX Falcon Heavy. While SpaceX has a huge head start in developing reusable orbital rockets, Blue Origin has a positive track record with its suborbital rockets and will likely prove to be a strong competitor to SpaceX in the near term.

Other rocket systems, such as the Space Launch System being developed by NASA to be a true successor to the Saturn series rockets that sent NASA astronauts to the moon, and the United Launch Alliance (a joint venture between Boeing and Lockheed Martin) Atlas and Vulcan series rockets, are not currently reusable, but can deliver larger payloads than the current SpaceX rockets.

Single Stage Takeoff and Landing

The growing number of rocket companies show a lot of promise in bringing down the costs of sending people and equipment into space, but there are other technologies that could reduce the costs of spaceflight even further. Current jet engines can typically only fly as high as about 30,000 feet. Specialized planes, like NASA's Helios, can fly even higher up, but none can fly directly into space. This is because the air is too thin at such heights for a plane's airfoils to create any lift. At this point, the only way to go higher would be to switch to a rocket engine. This is currently impossible, but with recent advances in the 30-year long U.K. project called the Synergetic Air Breathing Rocket Engine (SABRE), that may soon change.

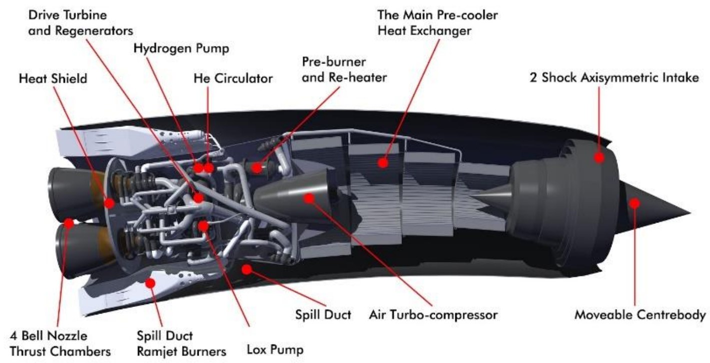


Image 5: Synergetic Air Breathing Rocket Engine
Credit: Reaction Engines

The SABRE engine will be able to switch from a jet-engine mode to a rocket-engine mode in the earth's upper atmosphere, enabling spacecraft that can take off from the earth like an airplane, and fly into orbital space. This will not only decrease the amount of time it takes to get from one part of the globe to another, it will make rockets nearly obsolete for human spaceflight. Rockets will still be necessary for carrying heavy payloads into space, but human space travel will have a much more comfortable approach.

Satellites and Probes

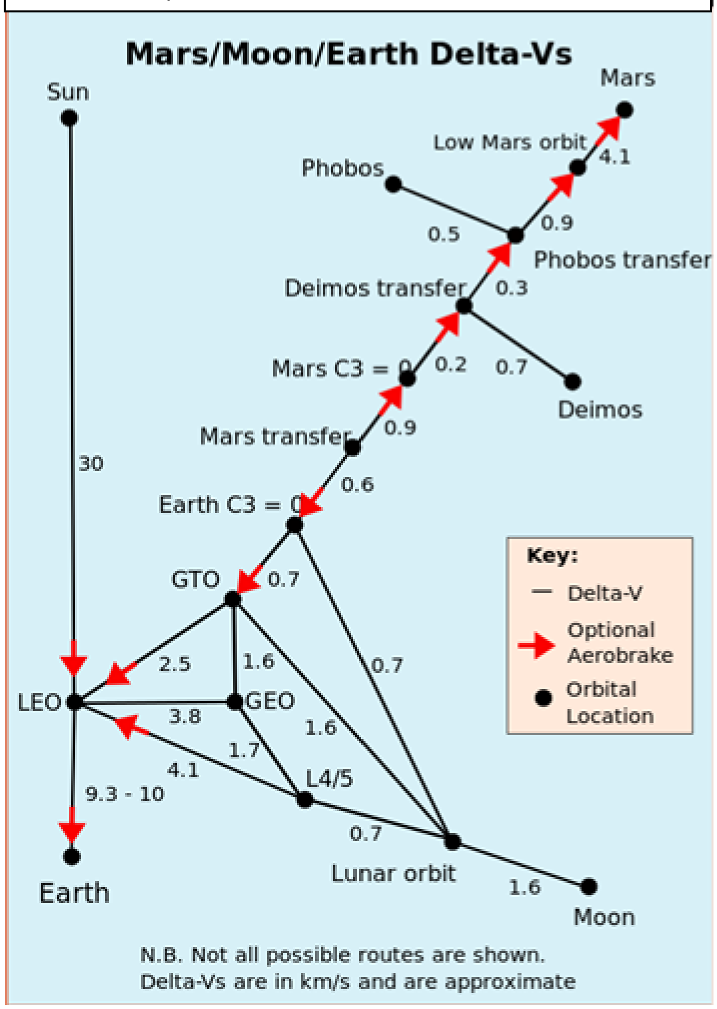
Most consumers only think of satellites as how they get the tv service, or GPS, or how the weatherman can make his predictions. These are all true, but satellites and space probes are also key to enabling human expansion into space. Autonomous space vehicles will be important precursors to any human settlement, either to begin extracting resources, establish settlement structures, or both. This paper will examine the use of space probes to harvest resources from asteroids, and the use of a satellite network relay system for far-off communications.

Image 6: Planetary Resources Arkyd 6 satellite, scheduled for launch late 2017.
Image Credit: Planetary Resources.

Asteroid Mining – Exploratory satellites

Until the spring of 2012, the very notion of asteroid mining was considered by most to be science fiction, or perhaps a development of the far-off future. But the founders of Planetary Resources thought differently. Chris Lewicki and other NASA engineers felt that it was time for the private sector to grow its involvement in the space sector, and they had just the idea of how it could be done. The company has secured $21.1 million funding from the United States government, another €25 million from Luxembourg, and even more from private investors. Planetary Resources' near- term plan is to develop satellites with specialized instruments to use spectroscopy and other methods to prospect asteroids and determine their chemical composition for consideration as a target for the first real mining mission. The first test satellites are already in orbit, and an entire constellation of satellites is being planned and an asteroid prospecting mission has been announced to be launched by 2020.

Figure 2: A diagram of the Delta-V required to travel to different planetary bodies in the near solar system.
Credit: Wikipedia



Asteroid Mining – In-situ Resource Utilization

Once Planetary Resources has identified a promising test asteroid, they plan to send a probe to take physical samples to return to earth for study, with the goals of determining the asteroid's true composition, and how best to extract any resources found therein. Once an effective mining operation is developed, Planetary Resources and similar companies that may arise will send fleets of asteroid probes that will harvest asteroids and establish bases of operations in or near asteroid clusters. Some of these resources will be returned to earth for manufacturing or study, but the ultimate goal is to be able to harvest and process metals, minerals and water found on these asteroids in-situ (meaning, while in space).

By having the ability to harvest resources in-situ, the cost of going into space is not only reduced, but becomes negligible as just another operating expense necessary to conduct business. In-situ resource utilization has the added benefit of reducing the carbon footprints of both mining and heavy manufacturing because these activities can be shifted from an earth environment where it inevitably affects some ecosystem, to a sterile space environment in which the only ecosystems are the enclosed ones that humans take with them into space.

There is estimated to be more nickel, iron and platinum type metals in a single eight-kilometer metal-type asteroid than has ever been mined in human history. And carbonaceous asteroids will provide plentiful sources of water, which may be used for human consumption, radiation shielding, or even be split into molecular hydrogen and oxygen for fuel and artificial atmosphere generation.

With the development of reusable rockets making it cheaper to get to space, as outlined above, asteroid mining becomes an even more profitable venture. As the figure to the right shows, it is much easier to get almost anywhere in the solar system once out of the earth's gravity well, including traveling to asteroids or to the moon.

Communication and Transportation Relays

Before space stations and planetary bases become a commonplace thing, a reliable communications network will also be necessary to put into place. Communications between earth based entities and entities in near earth orbit are straight forward, but the further away from earth that bases get established, the more necessary a communications relay system, most likely using high powered lasers, will become. This is especially true for any habitations built on Mars, which every two years can be found on the opposite side of the sun. When this is the case, it will be impossible to send a direct signal to Mars either because the sun is directly in the path of travel for the laser, or it will cause significant interference with the signal.

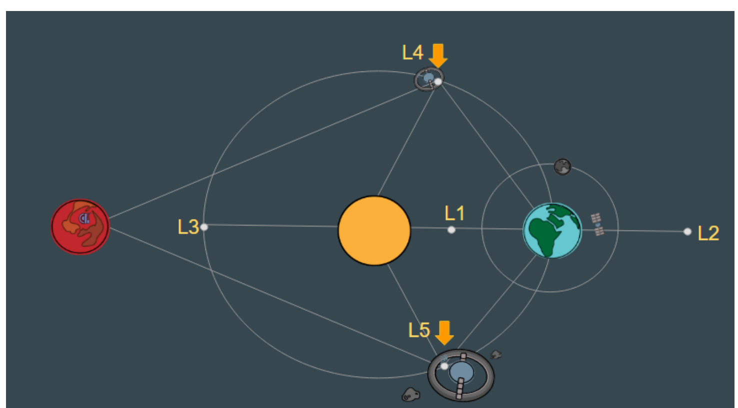


Figure 3: Earth-Mars Communication and Transportation Relay
Credit: Whitney Lunny

One potential solution to this problem would be to place relay stations at the earth-sun LaGrange points 4 and 5. It would be possible to only use one of these points, but redundancies in space systems will be necessary features into the foreseeable future. An additional advantage of using the L4 and L5 points as a communications relay is that the relay itself can be added to. These points have existing populations of Trojan asteroids that could be harvested for resources (K. K. John) and built into a space station that could act as a waypoint for earth to Mars travel as such trips become more common place. These waypoints would increase the number of windows that travelers from earth must use to travel to Mars, instead of waiting every two years as currently must be done when sending exploration rovers.

Space Stations

This report will examine space stations in two contexts: true space stations, which are built in microgravity; and planetary bases such as may be built on the moon or Mars.

Microgravity Space Stations

Space stations built in microgravity, such as the ones that are proposed for L4 and L5, can be built in the form of a “torus”, or ring, to rotate in such a way that the generate centrifugal force to simulate gravity. Depending on the radius of the torus, and its speed, it could even be made to match the earth’s gravity. Several proposals were made during a joint study between the NASA Ames Research Center and Stanford University in 1975 would have used this method, such as the Stanford Torus and the Bernal Sphere (pictured right), would be 1.8 km in diameter or larger. The size of the torus would be necessary to minimize the Coriolis effect, and would also be able to house approximately 10,000 people. Other microgravity space stations following different design concepts may be built, but to simulate gravity, the only known method to do so in space is to use the Coriolis effect.

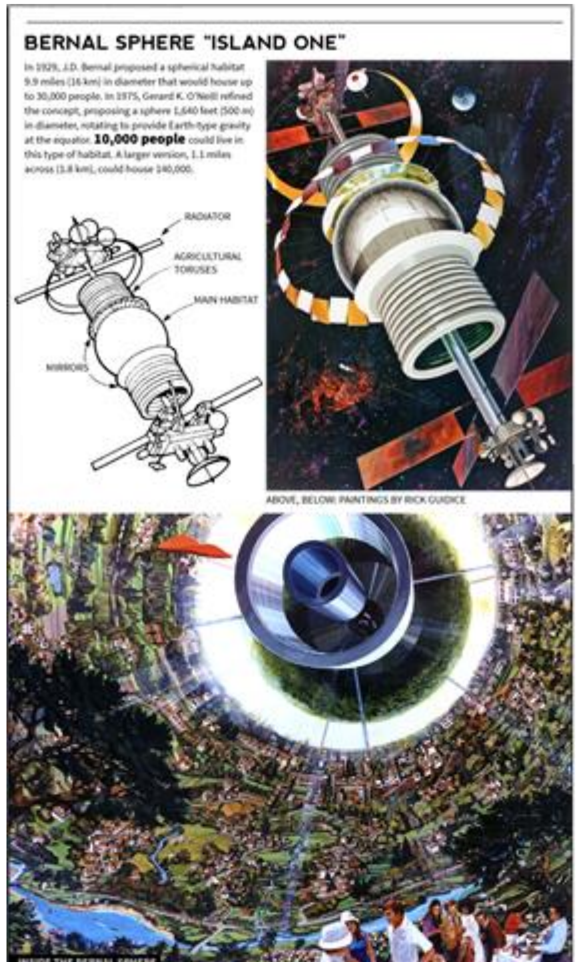


Image 7: Bernal Sphere Credit: Karl Tate

By strategically placing such space stations at LaGrange points between the earth and moon for lunar travel, and along the earth’s path around the sun for interplanetary travel, we begin to see a true distribution system that would enable a flow of goods and services from one point in space to another. These waypoints would be the necessary nodes of any true space economy, and would naturally become major trade route destinations that could grow into large cities in their own rite.

The biggest obstacle for humans to make such environments into a livable home will not be zero-gravity, but rather solar radiation. Outside of the earth's magnetic field, solar and cosmic radiation would be deadly without a reliable method of shielding humans. The best-known space radiation shield to date is water, which at three meters thick all around would be sufficient to block even the most powerful radiation sources. This water could be harvested from carbonaceous asteroids and cycled through a larger plumbing network for household use and crop growing efforts in addition to its purpose of radiation shielding. Some advances in material science, particularly with a superfluid with suspended particles of indium gallium alloy could potentially address the radiation shielding problem much more easily, but it remains to be seen if the substances radiation shielding effect could be scaled to such large applications.

Planetary Bases

Planetary bases would be easier to initially establish using existing technology than something like a Stanford torus, but would still come with challenges of their own. By establishing a base on a planetary sized body, humans committing themselves to life in yet another gravity well. While that is much better for bone and muscle strength than microgravity, it also reintroduces the initial difficulty of getting into space in the first place: the rocket equation (explained under Reusable Rockets). The moon and Mars have much less gravity ($1.6 m/s^2$ and $3.7 m/s^2$, respectively) than the earth does, and so would not be nearly as challenging to escape as the earth is. But during initial exploratory efforts, this will still pose a significant challenge, especially in the event of a disaster. Military models of redundancy systems will be just as critical as on a space station.

But once a base of operations is established, the people living in planetary bases will have a huge advantage over those living in space stations, they will have an entire planet worth of resources right at their feet. Even the dirt that they walk on will be a valuable resource, which can be used to make cement for 3D printed structures or converted into soil for growing crops, or even replicating an earth based ecosystem on another planet.

Conclusion

Humanity faces significant challenges in its goals to expand beyond the earth's sphere, but these challenges are not insurmountable. Many of the obstacles currently in place are already being overcome, rockets are becoming cheaper to send up, and soon robotic space probes will be ready to begin harvesting metals and water to build human habitations before humans even get there.

With the establishment of a supply chain system to facilitate the transfer of humans, materials and information, not only will humans be able to colonize space for good, but they will be able to thrive, expand, and build an entire civilization out amongst the planets and moons of the solar system.

It is not only possible for humanity to colonize the outer space of the solar system, but it will open whole new realms of possibility for the development of humanity as a society and as a species. It is now time for businesses, entrepreneurs and governments to be considering what their contributions could be to the development of this system, because it is not a question of if it will come to be, but when.

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