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DEEP SPACE INDUSTRIALIZATION: Key To Sustainable Exploration, Development and Settlement of the Solar System

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Abstract

Recent developments related to deep space exploration and development have raised the question of whether the paradigm shift that many people have been expecting, from space exploration to space development and industrialization, is finally occurring. These recent events include Space Exploration Technologies (SpaceX) announcement that they have been contacted by two wealthy individuals who would like to travel around the Moon within the next two years and a recently reported story of Jeff Bezos' proposal to the Trump Administration to offer cargo delivery services to the Lunar surface (Blue Moon) by mid 2020 as part of a public/private partnership with NASA. In addition Bob Bigelow, founder of Bigelow Aerospace, has announced the capability and desire to put a crewed space station in orbit around the Moon in this same 2020 time period. Moon Express has also recently announced that they are fully funded for their attempt to land their robotic probe on the lunar surface at the end of this year, not only to win the Google Lunar XPrize but also to jump start their lunar mining efforts.

On the international front the Grand Duchy of Luxembourg has established a 200 million euro fund to invest in space mining companies with the aim of making Luxembourg the European leader in deep space commerce. To date they have made investments in two companies; Deep Space Industries and Planetary Resources both of which were established to prospect and mine near Earth asteroids. Other counties such as India, China, Japan and even Israel are eying this high frontier for deep space commerce.

This paper will explore how these developments could help enable this deep space industrialization and jumpstart a thriving deep space economy. The role that NASA and the US government can and should play in this effort and the role of public/private partnerships will also be discussed. Finally, what these developments could lead to over the next 10-15 years will be analysed and the potential size of this deep space economy will be estimated.

Keywords: (space development, space industrialization, commercial space, space tourism, space settlement)

1. Emergence of a Deep Space Ecosystem

The space economy in 2016 was estimated by the Space Foundation to be $329 billion with the bulk of this coming from revenue associated with geostationary communications satellites[1]. But a recent report by the Goldman Sachs Group highlighted the potential for the development of new markets such as space mining:

> "We believe a new space renaissance is starting, where a positive feedback mechanism of exploration and budget allocation could fuel development of the space economy. Beyond growth, the market is also shifting towards the private sector, where corporations are replacing government agencies, enabling the later to venture further out while pushing boundaries of their own to create new businesses like space tourism, asteroid mining, and on-orbit manufacturing and satellite services. Scientists and Silicon Valley entrepreneurs claim the conquest of space is the next step for human civilization, but exploration leads the way and we believe a thriving space economy is the primary path to realizing it."[2]

Congress is also re-vectoring NASA to look beyond its traditional exploration role by adding new roles such as "to expand human presence throughout the solar system" and "enable a thriving space economy in the 21st century"[3].

The initial market for space commodities is not for delivery back to Earth but will most likely be more economically attractive for utilization in space. Hence the early markets for space commodities is directly linked to the development of a deep space (beyond geostationary orbit) ecosystem. Conversely, this deep space ecosystem will be greatly accelerated if local materials can be mined, processed and economically transported rather than having to haul everything needed up from within Earth's deep gravity well. So how does such an ecosystem develop and what role(s) does the government, the commercial sector and new technology play in its emergence? To help answer this question it may help to take a look at historical examples of how this has happened in the past.

2. Opening New Frontiers A Historical Perspective

Over the last 500 years new frontiers, such as the American West were often opened by a combination of government and commercial entities using a public/private partnership model. Examples include the Virginia Company in 1609, the Erie Canal and the US transcontinental railroad in 1862. The Pacific Railroad Act of 1862 was signed into law on July 1 1862 by President Abraham Lincoln. The railroad would not only enable access the vast resources of the western frontier of the United States but also to reaffirm America's claim to the Pacific region of the US. The railroad was financed by a combination of US government 6%, 30 year bonds, at between $16,000 to $48,000 of bonds authorized for sale per mile of track that was laid and land grants of 6400 acres per mile to the railroad companies on alternating sides of the track[4].

Prior to the opening of the transcontinental railroad travel from New York to San Francisco could take many months (and much hardship) and cost ~$1000. After 1869 when the railroad was completed the trip took 7 days and a 3rd class ticket could be purchased for $65.00 and while not without risk it was much safer[5]. The railroad made it possible for farmers in the central and western portions of the US to grow and sell their crops to eastern markets at competitive prices. By 1880 the US had over 17,000 freight locomotives that carried over 23,000 tons of cargo and allowed the raw material of the west to be brought to the East Coast for processing[6]. Could the same model be applied to aerospace infrastructure development?

2.1 The Birth of Aviation

34 years after the completion of the Transcontinental railroad the Wright Brothers made their first heavier than air flight on Dec. 17th 1903. Their 3rd flight that day was 854 ft. flight and lasted only 59 seconds but with this milestone the world changed forever. But by 1915 the US had fallen far behind Europe in aviation technology. With Europe fully engaged in WWI and eager to regain aeronautical competitiveness the US Congress on March 3, 1915 established the National Advisory Committee on Aeronautics (NACA) "to supervise and direct the scientific study of the problems of flight with a view to their practical solution". Starting off with 12 unpaid members and an annual budget of $5000 the NACA in its early years was able to make major contributions to aviation. Some of these contributions included; passage of Kelly Airmail Act in 1925, passage of the Air Commerce Act in 1926, establishment of the Manufacturers Aircraft Association, establishment of the Bureau of Aeronautics in the Commerce Department and a number of technical achievement from their newly established aeronautical laboratory in Virginia[7].

The Langley Memorial Aeronautical Laboratory was started in Hampton Virginia in 1917. Completed and commissioned in 1920 this new laboratory performed foundational aeronautical research in the 1920-30s dealing with multiple aspects of aerial flight including; airfoil design, cowlings, propellers, icing and navigation. Between 1939 and 1946 four other facilities were built by the NACA, Ames Aeronautical Laboratory (1939), Lewis Research Center (1943), Wallops Flight Center (1945) and the Muroc Flight Test Center (1946). It was at the Muroc Flight Test Center in 1947 that the NACA/AAF funded Bell X-1 broke the "sound barrier" and opened another new era of aviation development. Following the X-1 NACA developed a series of high speed research vehicles that culminated in 1959 with the introduction of the rocket powered X-15 that ultimately achieved altitudes in excess of 50 miles and a top speed that still stands as a world record of mach 6.7 (4,520 mph).

NACA research not only helped the US to victory in WWII but also helped provide the technical foundation that the commercial air transport industry would build upon to become the world leader in aviation. Some of the other technical achievements created by the NACA include: the swept wing for high speed flight, the "area rule" for transonic flight and the blunt body concept for reentry vehicle returning from orbit. When NASA was formed in 1958 all of the NACA facilities and personnel were folded into NASA. Lets look at how the commercial air transport industry benefited from these government investments.

On Jan. 1, 1914 the first commercial flight took place by seaplane between St. Petersburg and Tampa Florida.

Fig. 1. 1st Commercial US flight Jan. 1, 1914

The flight lasted 23 minutes, cost $400 and carried one passenger; the era of air travel had begun[8]. In the

1920's regularly scheduled commercial flights using Ford and Folker Trimotors these early airlines such, as United, TWA and American offered adventurous travelers the option of traveling by air. The loss of a Ford Trimotor by TWA in 1931 lead to the development and introduction of the Douglas D-3. This 21 passenger all metal twin engine aircraft made its first flight on Dec. 17, 1935, 32 years after that first flight at Kitty Hawk. It was the first true airliner and it revolutionized air transport cutting the time to get from New York to San Francisco to under 19 hours. It was comfortable, safe and economical. Over 16,000 were built for both civilian and military customers (the vast majority for the military in WWII).

Fig. 2. DC-3/C-47 entered service in 1936

After the war these planes were surplused and sold to commercial carriers. This and the huge number of airbases that had been built around the world to support the war effort, which after the war were converted to civilian use, contributed to a major surge in air travel and air commerce after WWII. But the 1957 introduction of the Boeing 707 was what really started the modern era of international air commerce and reduced the flight time from New York to San Francisco to about 5 hours. The development of these airplanes leveraged the technology and wind tunnel facilities that were provided by the NACA/NASA and led to the development of a fleet of aircraft of increasing size and efficiency including the Boeing family to jet transports: the 727, 737, 747, 757, 767, 777 and most recently the 787.

On Jan. 1st, 2014, 100 years after that first passenger flight the International Air Transport Association estimated that 8 million people flew on nearly 100,000 flights world wide that day. In 2013 some 3.1 billion people flew by air and in addition to passengers these planes carried an estimated 50 million tons of cargo valued at $ 6.4 trillion (or 35% of the value of goods traded internationally)[9]. The aviation industry supports more than 57 million jobs and generates $540 billion in direct economic activity.

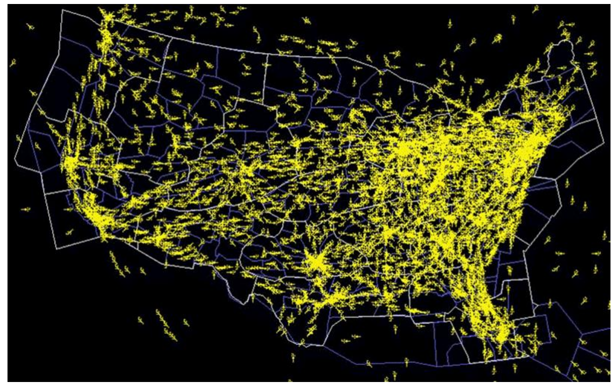

Fig. 3. US Daily air traffic display

3. Need For Regulation

The early days of aviation resembled the "Wild West" with little or no regulation but by the mid 1920's "aviation industry leaders believed the airplane could not reach its full commercial potential without federal action to improve and main safely standards. At their urging, the Air Commerce Act was passed in 1926". This legislation established a new Aeronautics Branch within the Department of Commerce. The new agency was charged with issuing and enforcing air traffic rules, licensing pilots, certifying aircraft, establishing airways, and operating and maintaining aids to air navigation. This aeronautics branch would eventually evolve into the Federal Aviation Agency (FAA) in 1958 and later in 1967 when the Department of Transportation was established the newly renamed Federal Aviation Administration made part of this new Department. The FAA now controls over 25,000 scheduled flights per day keeping track of over 6000 aircraft in its air traffic system with exceptional efficiency and safety[10]. Could the dramatic growth that the aviation industry has experienced over the last century be matched or surpassed by a deep space industrial revolution?

4. Evolving Role of Government in Space

On February 1, 2003 the Space Shuttle Columbia disintegrated during reentry killing all 7 crewmembers. This tragic loss shocked the nation and the aerospace community. In August 2003 the Columbia Accident Investigation Board submitted their report on the accident. On January 14, 2004 President George W. Bush laid out his Vision For Space Exploration (VSE). The VSE outlined several NASA objectives including completion of the ISS, retirement of the Space Shuttle once the ISS was complete and a sustained and affordable human and robotic program to explore the solar system and beyond, starting with the Moon as soon as 2015. During the intervening 14 years several of these goals were accomplished. The ISS was completed in 2011 and the Space Shuttle was retired a few months later. But we have not sent Americans back to the lunar surface and NASA currently has no plans to do so. But with the retirement of the Shuttle imminent

NASA needed a way to get supplies and crew to the ISS after the Shuttle stopped flying. To meet this need NASA implemented the Commercial Orbital Transportation Services (COTS) program.

The COTS program was announced by NASA on Jan. 18, 2006 with the stated purpose of demonstrating the capability of commercial companies to deliver cargo to and from the ISS. On August 18, 2006 Elon Musk's Space Exploration Technologies (SpaceX) was selected as one of two companies to enter into a funded Space Act Agreement (SAA) with NASA. Under this agreement SpaceX was awarded up to $278 million if all of its milestones were met, but SpaceX was only paid for completed milestones so risks that had been traditionally been assumed by NASA were now transferred to the company. However with this new type of agreement NASA was able to significantly reduce its oversight requirements and give SpaceX much greater flexibility of how it achieved its milestones. This turned out to be a true win/win arrangement.

As part of the COTS program SpaceX designed built and tested their Falcon 9 rocket, the Merlin engines that power it and the Dragon capsule that would carry the cargo to and from the ISS. The Falcon 9 reached orbit on June 4, 2010 on its first attempt.

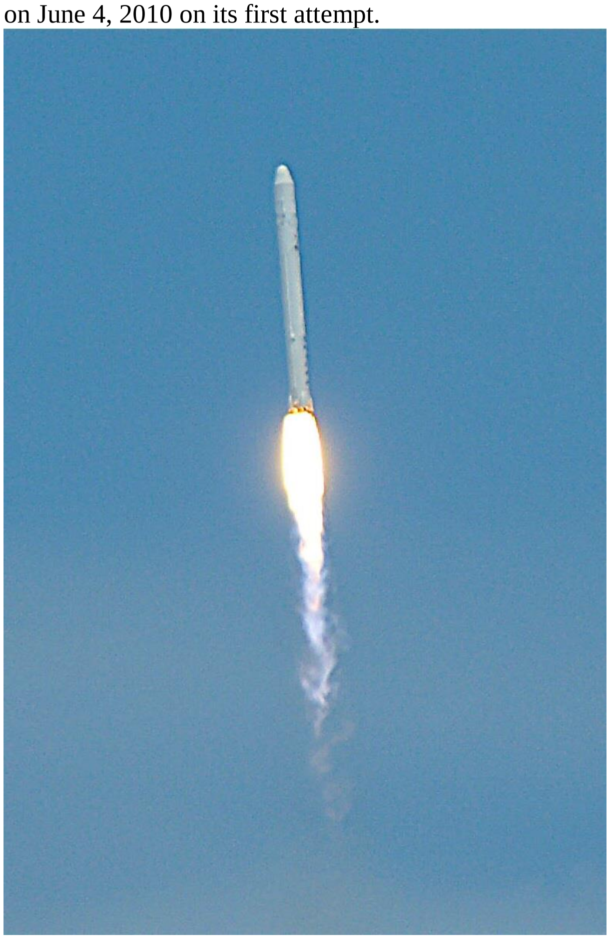

Fig. 4. Falcon 9 launch with Dragon Capsule

6 months later, on the second Falcon 9 launch, the SpaceX Dragon capsule flew to orbit and successfully returned, splashing down under parachute in the Pacific Ocean off the coast of Southern California. In May 2012 SpaceX successfully berthed the Dragon capsule completing the last of their COTS milestones. As a follow on to COTS in 2008 SpaceX won a $1.6 billion fixed price contract to send 12 cargo flights to the ISS as part of NASA's Commercial Resupply Services (CRS) program. SpaceX has completed its original contract and has now been awarded additional cargo flights as well as a $2.6 billion fixed price contract to upgrade their Dragon capsule to deliver NASA astronauts to and from ISS starting in 2018. Boeing has a similar contract to delivery NASA astronauts to the ISS starting in late 2018.

NASA HQ wanted to understand how SpaceX was able to develop the Falcon 9 for under $400 million when their own NAFCOM cost model estimated that using normal NASA cost plus contracting methodologies the cost would have been almost $4 billion [11]. But Musk's innovations go beyond cost savings. He has demonstrated repeated reusability on his Falcon 9 first stage booster and in the past two years he has successfully landed 15 stages either back at the launch site or out at sea on floating modified barges. SpaceX has also successfully relaunched and recovered two of these flight proven boosters. This reusability not only offers the potential to significantly increase the flight rate but also to enable major cost reductions. Elon has stated that he invested about $1 billion to achieve this level of reusability and he financed all of this from within the company with no government funding of this project.

An equally important capability that SpaceX has been able to successfully demonstrate is the ability to incrementally but substantially improve the performance of the Falcon 9 while still flying it. The initial lift capability of the Falcon 9 V1.1, which first flew in 2010, was 13.8 MT to LEO. In December 2015 SpaceX launched their upgraded Falcon 9 Full Thurst (FT)[12] which has an increased launch capacity to 22.8 MT to LEO. In addition to 1st stage reusability some of the other major upgrades that were incorporated into the new design included:

- Subcooled propellants and enlarged 2nd stage tanks
- Upgraded structure in the first stage and interstage
- Reconfiguration of 9 1st stage engines to octaweb
- Addition of grid fins and landing legs
- Major upgrades to the Merlin 1D engine

SpaceX's final upgrade to the Falcon 9 (the block 5) which will fly in early 2018 is designed to have not only increased payload capability to orbit but also an amazingly quick turnaround capability for the first stage that enables the first stage to be reflown within 24 hours! While SpaceX has been very successful with its launches, it has experienced two failure, the CRS 7 cargo delivery flight to the ISS in June 2015 and a rocket carrying a Israeli satellite that exploded during propellant loading for a static fire test in Sept. 2016. But in both cases SpaceX was able to quickly determine the cause of the failure, take corrective action and quickly return to flight.

Fig. 5 SpaceX Falcon 9 1st stage landed on barge

Elon Musk has a stated goal of not only traveling to Mars, he plans to establish a thriving city on Mars[13]. To accomplish this he needs a bigger rocket and he needs to greatly reduce the cost, so to that end SpaceX has two additional heavy lift rockets in development. The first is the Falcon Heavy, which consists of 3 Falcon 9 first stage cores strapped together, which is scheduled to launch by the end of 2017. The Falcon Heavy will carry up to 63.8 mt to LEO. The second is the BFR (Big Falcon Rocket), which should be operating early in the next decade. The BFR will be a much larger vehicle than the Falcon 9 with a 9 meter core and it will be the largest rocket that has ever been launched (with a payload capability estimated to be greater than 160 mt) and it will be fully reusable.

Elon is not the only person with big space visions who believes that reducing launch costs through reusability and increased flight rates is the key to expanding human civilization throughout the solar system. Amazon founder Jeff Bezos, one of the worlds richest individuals, has a vision of million of people living and working in thriving communities beyond the Earth[14]. He wants to move all big polluting, energy intensive industries off the Earth and into space and to rezone the Earth as residential and light industrial. Jeff also believes that incorporating reusability to dramatically reduce launch costs is the key and he in 2000 he founded his space company Blue Origin to accomplish this.

Initially focused on suborbital spaceflight Blue Origin has developed the New Shepard booster and capsule to achieve this goal. On Nov. 23rd 2015 the unscrewed New Shepard vehicle flew to an altitude of 333,000 ft. (101 km) and then successfully landed back at the launch site. That same New Shepard vehicle flew to space a total of 5 times and returned safely back to Earth ready to fly again.

Fig. 6. Blue Origin New Shepard liftoff

But Bezos has orbital aspirations and is now developing his New Glenn two/three stage vehicle that will be partially reusable and will deliver 45 MT to low Earth Orbit (LEO). The New Glenn vehicle will be built in a new 750,000 sq. ft. production facility that is being completed in Florida at Exploration Park at the Kennedy Space Center and the launchs will take place nearby at Launch Complex 36. The new Glenn vehicle will take both NASA astronauts and commercial space travelers to LEO and beyond. So between SpaceX and Blue Origin in the next three years we could see the number of launches increase dramatically to hundreds of flights per year.

Fortunately, the regulatory environment is also evolving to keep up with these changes. In 1984 Congress established the Office of Commercial Space Transportation (AST) in the Office of the Secretary of Transportation and in 1995 this office was transferred to the FAA. AST is tasked with regulating the US commercial space transportation industry, to ensure compliance with international obligations of the United States, and to protect the public health and safety, safety of property, and national security and foreign policy interests of the United States. But they also have the responsibility to encourage, facilitate and promote commercial space launches and reentries by the private sector. Every commercial (non government) launch or reentry in the US or by a US company, that takes place anywhere in the world, requires license from FAA/AST. AST also licenses commercial spaceports and there are currently 10 licensed spaceports in the US with several more pending approval[15].

With all of this investment in large, reusable launch vehicles and an enlightened and supportive regulatory environment many experts expect the cost of launching payloads to orbit to plummet to that magical but historically illusive goal of $100/lb ($220/kg). The key to low launch cost is not only reusability but also flight rate. How quickly can you turn the vehicle around and launch it again with paying customers? So what opportunities would low cost launch offer that could lead to a deep space industrialization revolution?

5. Building Blocks For A Deep Space Industrial Revolution

The International Space Station (ISS) is the first element of permanent (useful life of at least 2 decades) piece of space infrastructure. The ISS has been continuously occupied since 2000, has a crew of 6 and ~930 cubic meters of pressurized volume. The ISS was developed as an international partnership between the US, Canada, Russia, Japan and ESA (European Space Agency). To date the investment to develop, construct and operate the ISS is in excess of $100 billion.

The 2005 NASA Authorization Act designated the American portion of the ISS as a national laboratory and designated that half of the facility should be made available to non-NASA researchers. In 2011 NASA selected the Center for Advancement of Science in Space (CASIS) to oversee the ISS National Lab. In addition to CASIS NASA has also developed partnerships with other commercial companies to assist them in providing access to the ISS to companies and academic institutions seeking to do research and technology development in space. These companies include Nanoracks, Made In Space, Space Tango, and Techshot. Research is currently underway on the ISS covering a wide variety of topics including, life science, biotech, material science, Earth observation, advanced communications, data storage and supercomputing. As the barriers to conducting operations in space decrease in both cost and time it opens up the potential for not only new research but also for manufacturing in space.

Simple put the idea of space manufacturing is to take materials to space, process it or add value in some other way, then bring the processed material back to Earth and sell it at a profit. The advent of space manufacturing could offer the high demand for spaceflight that is required for reusable launch vehicles to reach their full economic potential. There are several attractive candidates for space manufacturing on the horizon but one candidate that has attracted a lot of attention lately is an exotic optical fiber called ZBLAN.

ZBLAN is a heavy metal fluoride glass that has exceptional optical properties including a very broad optical range from 0.3 to .7 microns and an optical attenuation that may be as much as 2-3 orders of magnitude better than silicon fibers. One of the barriers to manufacturing ZBLAN on Earth is that in a 1g environment crystallites tend to form in the fiber which degrades the optical properties but in microgravity appears to greatly reduce the formation of these crystallites [16]. At least three companies, Made In Space[17], FOMS Inc. and Physical Optics Corporation, are currently planning to test manufacture ZBLAN on the ISS. If they are successful then orbital facilities that can house the volume production of ZBLAN would need to be found. Fortunately there are at least two companies that are planning just this type of facilities: Bigelow Aerospace and Axiom Space LLC.

Bigelow Aerospace was founded in 1998 by Bob Bigelow a real estate developer and hotelier who owns Budget Suites of America[18]. The goal of Bigelow was to focus on the other part of the space transportation equation, the destinations. Rather that developing a better way to get to space Bigelow intends to provide a destination to go to once you get there. In 2000 Bigelow licensed NASA's Transhab expandable technology from the Johnson Space Center (JSC). Transhab was developed to provide expandable habits to enable NASA Mars exploration[19]. Transhab modules can be folded up to fit into rocket shrouds and once in space then can be inflated (Bigelow prefers the term expanded). Since 2000 Bigelow has invested over $250 million of his own money to mature the Transhab technology and flight test it. In 2006 and 2007 Bigelow launched Genesis I and II into orbit. These small technology demonstrators are each 11.5 m^3 (410 ft^3) and have been operating successfully in orbit for over a decade. In 2016 the Bigelow Expandable Activities Module (BEAM) was launch in the trunk of a SpaceX Dragon spacecraft and was successfully attached to the ISS and expanded to its full size of 16 m^3 (565 ft^3).

Fig. 7. BEAM attached to the ISS

This work was carried out under a $17.8 million contract with NASA who also paid for the launch. The purpose of the 2 year BEAM mission to validate the feasibility of utilizing expandable technology to enable astronauts to live and work in these modules. More than half way through the mission the BEAM is working as planned. But Bigelow has bigger plans for this technology.

Bigelow is currently developing the B330 module which will weigh about 20 mt and provide 330 m^3 (11,700 ft^3) of pressurized volume. Bigelow is constructing two B330s and plans to have them ready to deploy to orbit in 2020 to enable microgravity research as well as habitation for a variety of customers. Three B330s would provide the equivalent pressurized volume as the ISS's 916 m^3 (32,333 ft^3). Bigelow has plans to deploy his modules not only in Earth orbit, but also in deep space and on the surface of the Moon and Mars.

Axiom Space LLC was founded in 2016 by former NASA ISS program manager Mike Suffredini and Axiom Space also wants to be a prime space destination [20]. Axiom's aspirations are similar to Bigelow's but they are using a more traditional hard shell construction for their modules. They also plan to have their first modules ready to launch in 2020 and plan to house astronauts but by the mid 2020s they expect space manufacturing to be the dominant customer. Initially they plan to have their module attached to the ISS and later transition to a free flying facility.

What does all this add up to? By 2020 (or soon there after) if everything goes according to plan the US will have two next generation, at least partially reusable heavy lift commercial launch vehicles (Falcon Heavy and New Glenn), two crew capsules capable of taking astronauts to and from LEO from US launch sites (SpaceX Dragon 2 and Boeing Starliner) and two destination in addition to the ISS capable of carrying out research and a variety of other services including tourism (Bigelow and Axiom Space). This does not even take into account the international space activities that will be occurring during this time period or those still in "stealth mode". This looks like a perfect storm for deep space industrialization so lets explore how this might come about.

6. Back To The Moon

NASA's last mission to land on the lunar surface, Apollo 17, departed from the Moon on Dec. 14, 1972, no one has been back since. In fact no human has been more than 400 miles above the surface since Gene Cernan, Harrison Schmidt and Ron Evans returned to Earth on Dec. 17, 1972 (69 years after the Wright Brothers first flight), but that could be about to change. The Apollo lunar landings collected and brought back about 380 kg (838 lbs) of lunar material for analysis. This provided a wealth of data about lunar composition but only in the equatorial regions where the 6 Apollo landings took place. Later lunar orbiter science missions by the U.S., Japan, India and China produced data that indicated the possibility of large quantities of water at the lunar poles. To find out for sure if there was water there in 2009 NASA launched the LCROSS mission[21]. Analysis of the ejecta from the LCROSS impact zone showed that it consisted of 5.6% water ice (+/- 2.9%) as well as other scientifically interesting and commercially useful volatiles including; carbon monoxide, hydrogen sulfide, carbon dioxide, sulfur dioxide, methane, and formaldehyde. But can these resources be extracted and if so at what cost[22]?

The Google Lunar X prize (GLXP) was established in 2007 to encourage commercial interest in returning to the Moon by offering a $20 million prize for the first team to land on the surface, travel 500 m and send back HD pictures and video. Government support for a team was limited to 10% of the mission cost. This generated a great deal of interest around the world but while it is technically challenging to land on the Moon the biggest challenging by far for the teams has been raising the capital to fund the trip, primarily buying the launch. Due to this difficulty the deadline for winning the prize has been extended several times and now the competition is set to expire on March 31st, 2018.

In 2013 NASA initiated the Lunar CATALYST program to enter into non-reimbursable (no exchange of funds) SAA's with commercial companies that had plans for sending robotic landers to the lunar surface. The purpose of these SAAs is to encourage the development of robotic lunar landers that can be integrated with U.S. commercial launch capabilities to deliver payloads to the lunar surface. While NASA does not provide direct financial support as they did in COTS, the companies would have access to NASA facilities, test equipment, expertise, and software. The three companies that were selected to participate were Astrobotics Technology, Masten Space Systems and Moon Express.

There are still 5 teams in the competition and several of the teams that are longer participating are still planning to land on the Moon. Several of these companies are offering cargo delivery to the lunar surface. Astrobotic is one of the former GLXP contenders that plans to land on the Moon in 2019 and is offering to carry customer payloads to the surface for $1.2 million/kg[23].

Fig. 8. Astrobotic Peregrine lander

Moon Express is still participating in the GLXP but has greater ambitions with multiple missions to the Moon planned starting in 2018 and with a sample return mission planned for 2020. One of their key goals of Moon Express (and others) is to mine the poles of the Moon to extract water and other precious resources[24]. One question that many people ask is why mine lunar water?

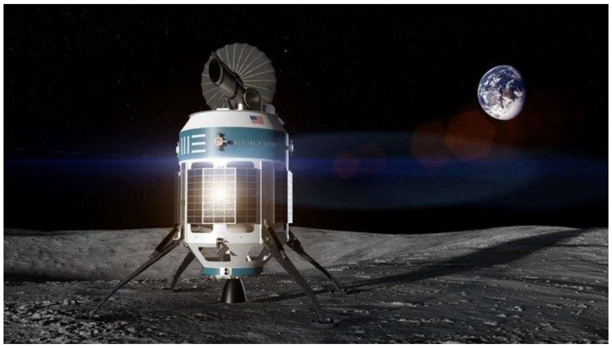

Fig. 9 Moon Express MX-1 lunar lander

Water ($H_2 0$) is composed of two common but very useful elements hydrogen (H) and oxygen (O). Oxygen is necessary for most life forms including people and any plans for expanding human civilization beyond the Earth will require this vital element. But oxygen when combined with hydrogen is the highest performing chemical rocket fuel currently available. The main engines of the Space Shuttle utilized this propellant combination and it produced a vacuum equivalent specific impulse (I_{sp}) of 454 sec. There are other fuels that can be produced from lunar materials. One of the more attractive propellants to make is methane (CH^4). Methane can be made using the Sabatier process by taking carbon dioxide (CO^2) and combining it with hydrogen at an elevated temperature of 300-400 °C which then produces methane and water. While methane does not have as high a performance as hydrogen in terms of rocket performance it has two important advantages, liquid methane is much denser than liquid hydrogen 0.42 g/cc for methane vs 0.07 g/cc hydrogen and methane liquefies at a much higher temperature than hydrogen (-181°C vs -253 °C).

7. Legal Authority

In 1967 the Treaty for the Peaceful Uses of Outer Space Article 2 states, "Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." Over the intervening years there has been a lot of discussion on just exactly this means as far as extraction and sale of space commodities.

On Nov. 25, 2015 the U.S. Commercial Space Launch Competitiveness Act was signed into law. Title IV – Space Resource Exploration and Utilization addresses this question of ownership in section 51303 which states "A United States citizen engaged in commercial recovery of an asteroid resource or a space resource under this chapter shall be entitled to any asteroid resource or space resource obtained including to possess, own, transport, use, and sell the asteroid resource or space resource obtained in accordance with applicable law, including the international obligations of the United States." The analogy that is most applicable is terrestrial rules for fishing in international waters. The fisherman does not own the ocean or the fish until the fish is caught at which time they do now own the fish and can process and sell it. Luxembourg has recently passed it own legislation regarding private ownership of space resources that took effect on August 1, 2017[25].

8. Reusable Space Infrastructure

Just as reusability is key to reducing the cost of space launch from Earth it, along with ISRU (in situ resource utilization or living off the land) could be the key to opening up cis-lunar space for exploration and development. By harvesting propellant from the lunar surface and using it to refuel reusable lunar landers the cost of traveling to the lunar surface could be dramatically reduced. One company that is interested in improving access to the lunar surface is Blue Origin. A March 2, 2017 story in the Washington Post (which Bezos owns) described a proposal that Bezos had made to the new Trump Administration with regard to a lunar delivery system that he is proposing to partner with NASA to develop[26]. Bezos believes he can have a vehicle capable of delivering 500kg to the lunar surface in the 2020 timeframe doing for the Moon what he had done here on Earth with Amazon, delivering pretty much anything, just about anywhere. Bezos plans on improving the lunar landing capability of Blue Moon to at least 10,000 lb. (4545 kg).

Even traditional aerospace companies have visions of a thriving space economy that harvest and utilizes space resource. United Launch Alliance (ULA) is a joint venture between aerospace giants Boeing and Lockheed Martin. ULA builds and launches both the Atlas and Delta rocket families for government and commercial customers. In 2015 ULA introduced their Cislunar 1000 concept[27]. This concept describes how, over the next thirty years, the space economy could grown from its current level of ~$330 billion to $2.7 trillion and the number of people living and working in space could grown from 6 to 1000 or more. One of the key features of the ULA concept is the redesign of their upper stage from a single use (Centaur), expendable system to a reusable and refuelable space tug which could operate indefinitely (ACES). ULA also has developed a concept for using a modified version of the ACES vehicle (the XEUS) as a lunar transport vehicle that could carry cargo and people to and from the Lunar surface. The key to these concepts is the ability to store and refuel vehicles in space. This topic will be addressed again later.

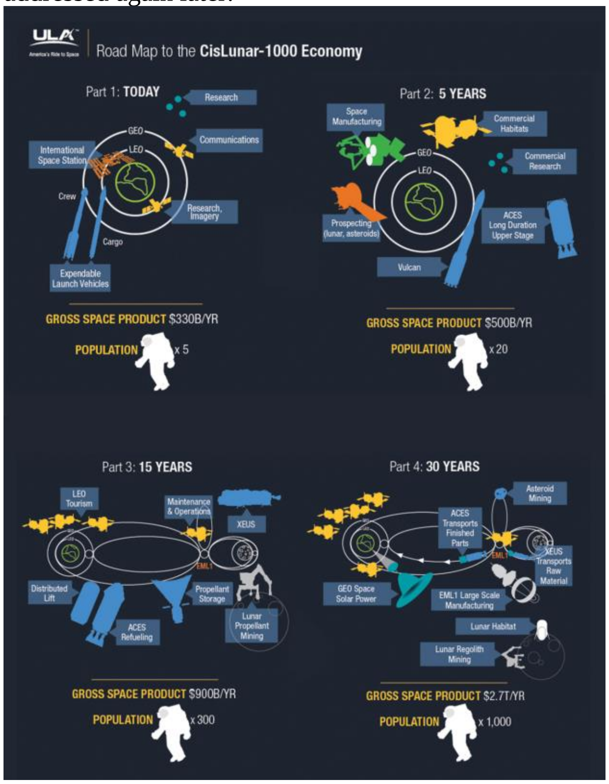

Fig. 10 ULA Cis-lunar 1000 roadmap

But the Moon is not just for robots and mining. Earlier this year Musk announced that two wealthy adventurers had contacted SpaceX regarding a trip around the Moon similar to what NASA did on Apollo 13. This trip would make use of the Falcon Heavy launch vehicle and a specially modified Dragon 2 capsule. No price was given for this mission but Elon stated this it could take place as early as the end of 2018 and that he believed that there were other customers who would also be interested in such a trip.

Space tourism is not new (note - the preferred term is spaceflight participant). Dennis Tito became the first paying customer to fly to orbit in 2001 aboard a Soyuz rocket to the ISS for an 8 day stay. Tito is rumored to have paid $20 million for the flight and spent 6 months training in Russia and had to learn the language and pass a rather challenging test. Between 2001 and 2009 six other space flight participants are estimated to have spent between $20-40 million for a similar experience. Charles Simonyi liked the experience so much he fly twice, for 15 days in 2007 and 14 days in 2009. After 2009 no seats were available to private passengers because the Russians made much more sending NASA astronauts to the ISS. Since the retirement of the Shuttle the Soyuz has been the only access NASA for sending its astronauts to the ISS.. In 2015 NASA signed a deal with Russia to purchase 6 seats for $490 million or a whopping $81.7 million per seat. This is why NASA is very anxious for the Commercial Crew program to successfully fly astronauts to space in 2018. But Boeing and SpaceX will not only be selling seats to NASA, since they own and operate these spacecraft, they are able to sell them to who ever has the desire and the money to do so. Which begs the question, how big will the space tourism market be and how long will it take for it to develop?

At last years IAC in Guadalajara Elon Musk presented his concept for establishing a thriving community on Mars starting as early as 2025 (as we mentioned earlier). During his presentation he made the startling statement that his goal was to put in place the infrastructure such as the BFR that would allow him to offer trips to Mars for $200,000 or less! Lets assume that Elon is being optimistic that instead of getting to Mars for $200,000 you could just get to Earth orbit. At this price how many people would want to go?

A number of studies have been performed over the years attempting to estimate the market for orbital tourism at different price points. A study in 2000 estimated that a $1 million ticket price for a flight to orbit the number of people willing to buy a ticket world wide could be several million. Jeff Bezos thinks this is the case. The New Glenn vehicle that Blue Origin is developing will be capable of carrying NASA astronauts and other commercial passengers to orbit and beyond and with a 45 ton launch capacity it should be able to carry a serious number of people to and from space.

So the pieces are all coming together, the transportation system, the destinations, valuable materials, potential for tourism, an abundance of available resources. One essential missing piece might be an anchor customer for water (or hydrogen and oxygen) in space. NASA could be that anchor customer.

Once a vehicle is launched into Earth orbit using chemical propulsion the majority of the vehicle mass (>70%) to get to anywhere else; to the Moon, asteroids, or even out to Mars is propellant. Instead of carrying all of this propellant in a single launch vehicle it could be brought up in separate dedicated tanker vehicles that would rendezvous with the orbital vehicle to provide the additional propellant needed to get to the final destination. This propellant could be launched from the Earth but because the Earth's gravity well is 22 times greater than that of the Moon it takes a lot more energy to launch the same amount of propellant from Earth as compared to the Moon. So this is why mining the Moon for water has attracted so much attention.

A 2015 NASA funded study lead by NexGen Space LLC, concluded that if NASA could utilize propellant derived from lunar polar ice deposits that the number of Space Launch System (SLS) launches needed for crewed mission to Mars could be reduced from as many as 12 to only 3[28]. In addition to the lunar mining and processing facility a propellant/resource depot possibly located at EM (Earth/Moon) Lagrange point 2 a stable point located 50,000 km above the lunar surface on the far side of the Moon. Since the planetary orbits of the Earth and Mars only offer a favorable launch window every 26 months propellant could be transported from the lunar production facilities to the L2 depot and stored there until needed. When the Mars opportunity arrived the SLS upper stage would be filled with LOX/LH2 from the depot and then the journey to Mars would start. Prior to this the depot could be used for assembly/checkout of the Mars vehicle prior to departure.

Fig. 11. Space propellant depot concept

Near Earth Asteroids (NEAs) are another source of resources that could become accessible in the next decade. Companies such as Planetary Resources[29] and Deep Space Industries [30] have their sights set on harvesting space resources starting with water but also including such commodities as platinum group metals, rare earth elements. While these objects come close to Earth's orbit on an irregular basis the change in velocity (delta V)to reach some of these objects can be quite small which make them potentially attractive objects for mining. While this would be quite different than mining on the Moon these companies believe that asteroids are the preferred target. Only time and results will tell who is correct.

One concept that was funded by NASA proposes putting a bag around one of these small asteroids and then use concentrated sunlight to mine the water [31]. TransAstra is a southern California based company that has received several NASA award to study asteroid mining techniques. TransAstra studies results show how, with a single Falcon 9 launch, they could rendezvous with one of these asteroids water rich asteroids and harvest 100 tons of water and return the water to cis-lunar (in the vicinity of the Moon) space.

An additional piece to add to this picture is the potential revolutionary impact that additive manufacturing (aka 3D printing) in space could have on the space economy. Currently the size of structures that can be launched into space is limited by the size of the payload fairings of the rockets that are used to launch them. For example the launch vehicle with one of the largest fairings is the ULA Delta IV Heavy at 5m x 19.1 m (16.4 x 62.7 ft). For larger payloads they must be folded which can add weight and complexity. For example the Webb Telescope which will launch in 2018 on a Ariane 5 has a primary mirror that is 6.4 m (21ft) in diameter. To fit within the fairing the telescope must be folded up using a very complicated mechanical arrangement. The mirror is composed of 18 segments each 1.32m (4.3 ft) in diameter that must automatically unfolded and aligned each segment to the next to within 1/10,000 the thickness of a human hair. Very challenging. The current cost of Webb is just under $9 billion. But in the future what if systems like the Webb Telescope could be assembled in space or even manufactured in space! What would that enable us to do?

Made In Space and Tethers Unlimited are two companies that are being funded by NASA to develop large scale additive manufacturing in space. Made In Space received a Tipping Point award to fund development and testing of their Archinaut[32] concept. Tethers Unlimited received a Phase I & II NASA Innovative Advanced Concept (NIAC) award to explore the feasibility of producing kilometer sized structures in space using their Spider Fab[33] concept. The idea for both concepts is to combine robotics, AI and additive manufacturing to produce large space structures. Initially the feedstock for these systems will be brought up from Earth but in the future they could use materials from the Moon or NEAs. Another interesting option that is being evaluated by NASA and others is recycling some of the 6 million pounds of orbital debris that is currently orbiting the Earth, the majority of this material highly refined metals that could provide additional feedstock.

NASA and its partners are holding a $2.5 million competition[34] to build a 3-D printed habitat from local materials for deep space exploration, to support human exploration and development of the Moon, Mars and other destinations throughout the Solar System. The multi-phase challenge is designed to advance 3-D construction technology needed to create sustainable housing solutions for distant locations from local materials which can also be applied wherever low cost housing is needed here on Earth.

One of the potentially huge future space markets ULA analyzed in their Cis-lunar 1000 study was the development of orbiting space solar power (SSP) stations to beam electric power to Earth. The ULA analysis concluded that by far the best way to develop large SSP stations in GEO was to build them from materials derived from the Moon. The current concept for SSP put forth in a 2011 study by the International Academy of Astronautics, examined the feasibility of gigawatt scale orbital collectors that could self assembly. This study showed that if the trends in launch cost reduction continue SSP could soon be competitive with coal and natural gas powered energy generators[35]. This analysis showed that SSP stations could play a major role in developing a $2.7 trillion deep space industrial economy by the middle of this century while supplying Earth with clean, green, affordable global power.

In 1975 NASA Ames and Stanford University hosted a 10 week Space Settlement summer study with the American Association of Engineering Education as part of their summer facility fellowship program[36]. The goal of the summer study was to explore the economic and technical feasibility of building large space where 10,000 people could live and work. The output of the study was a torus shaped habitat 130 m (427 ft) in cross section with a diameter of 1790 m (5871 ft) rotating at 1 rpm located at EM L5.

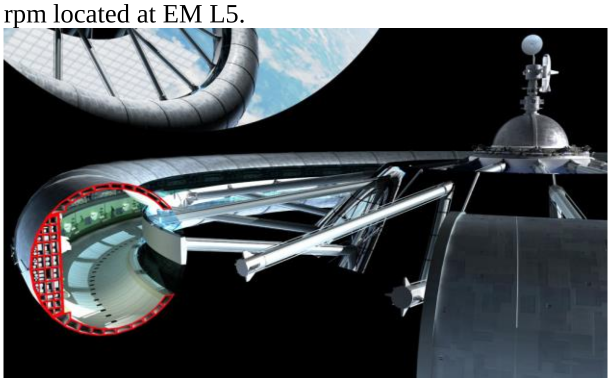

Fig. 12. Stanford Torus cutaway view

One of the leaders of this study, Gerard O'Neill was a physics professor at Princeton and he developed the idea of the large space colony as an exercise for his students. What surprised him was that the analysis that the students did showed that the concept was feasible even when scaled up to sizes which would house several million people. O'Neill, as the summer study technical director made this work from Princeton available for the study participants. The study concluded that space colonies were feasible but only if fully reusable launch vehicles could be developed to reduce the cost of getting to orbit and that the vast majority of the material for such a facility must be obtained from lunar or asteroidal materials. The results of the study were published in NASA SP 413 Space Settlements: A Design study and then in 1979 O'Neill published his now famous book "The High Frontier" for the general public.

The technological advances in not only rocket propulsion but also AI, robotics, supercomputing, machine learning, additive manufacturing, ISRU, nano-technology, synthetic biology and teleoperations, significantly reduce the barriers to achieving all of the space goals we have talked about including space colonies and SSP. These new and emerging capabilities greatly lower the barriers for the design, development and operation of these large space systems. The seeds that were planted in the minds of young dreamers from these early studies have taken root.

One person who was influenced by the ideas of O'Neill and the others in the 70's and 80's was a high school senior at Palmetto High in Miami who in his 1982 valedictorian speech talked of building cities in space for millions of people to live and work; this visionary senior was Jeff Bezos. Now, 35 years later Bezos, founder of Amazon and one of the worlds richest men, stands on the verge of having the wealth and technological capability, along with the other visionary space entrepreneurs, to make this dream a reality. Interestingly Bezos attended Princeton where O'Neill was still a professor and where he was elected president of the Princeton chapter of Students for the Exploration and Development of Space (SEDS). Just as happened with the American West, when people have ready and affordable access to places with vast resources and a supportive legal and regulatory regime, amazing things can happen. While a deep space industrial revolution and a thriving deep space economy may still seem like a dream to many more and more people are beginning to hear its "clarion call".

One additional element of this deep space economy being developed by Bruce Cahan from Stanford University and others is a Space Commodity Futures Trading Exchange. This concept was initially conceived at a workshop held by the National Space Society (NSS) and hosted by Steve Jurvetson at his VC firm Draper, Fisher, Jurvetson (DFJ) in Oct. 2016. Initial analysis indicates that the existing procedures for developing exchanges here on Earth such as the Chicago Mercantile Exchange or the London Metal Exchange could be extended to exchanges in space. The Exchange would allow potential customers to make their needs known and to allow suppliers to get a feel for what the market will be for resources they may be considering offering for sale prior to making the investment to go find and extract it. ULA has already set a president for this by stating their willingness to buy propellant in space. They have even established price points for propellant purchases and is offer to pay $3,000/kg in LEO, $1000/kg in GEO and $500/kg on the lunar surface[37].

9. Conclusions

Tremendous technical progress has been made in reducing the cost of access to space in the last decade. We now stand on the threshold of the next industrial revolution, this one in deep space. In addition advances in AI, robotics, additive manufacturing and other key technologies now enable the next generation of entrepreneurs to undertake projects that just a few years ago would have been just science fiction, such as mining the Moon and asteroids and hosting vacationing tourists on orbit or even on the Moon. All of the pieces seem to be coming together including the legal and regulatory framework which can support such an enterprise. Deep space industrialization is in a similar place to where the internet economy was 25 years ago, people had heard of it but where not sure if there was any money to be made there. Today the internet accounts for ~6% of U.S. GDP (gross domestic product), by 2040 we may be seeing the same results or maybe even greater for the thriving space economy that deep space industrialization is enabling.

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