



Editorial

Introduction to the Special Issue on using extraterrestrial resources to facilitate space science and exploration



To-date, all human economic activity has depended on the material and energy resources of a single planet, and it has long been recognized that developments in space exploration could in principle open our closed planetary economy to external resources of energy and raw materials. Recently, there has been renewed interest in these possibilities, with several private companies established with the stated aim of exploiting extraterrestrial resources. Space science and exploration are among the potential beneficiaries of space resources because they may permit the construction and operation of scientific facilities in space that would be unaffordable if all the required material and energy resources had to be lifted out of Earth's gravity. Examples may include the next generation of large space telescopes, sample return missions to the outer Solar System, and human research stations on the Moon and Mars.

These potential scientific benefits of space resource utilization were discussed at a Royal Astronomical Society (RAS) meeting held in London on 8 April 2016 on 'The Use of Extraterrestrial Resources to Help Facilitate Space Science and Exploration.' That meeting, a summary of which can be found in Ref. [1], was the inspiration for this Special Issue of *Space Policy*. Specifically, six of the eight papers in this Special Issue (i.e. those by James Carpenter et al., Ian Crawford, Colin McInnes, Martin Elvis, Phil Metzger and Vibha Srivastava) are peer-reviewed elaborations of talks presented at the meeting, and two papers (i.e. those by Marshall Eubanks & Charles Radley and George Sowers) were invited to complement the others from an industry perspective. It is also worth drawing attention to the fact that the main points covered by several papers presented at the RAS meeting (including those by Olivier de Weck on how lunar resources may help make human Mars missions more affordable [2], Paul Spudis on the Moon as an enabling asset for spaceflight [3], and Jim Keravala on the activities of The Shackleton Energy Company [4]) have already appeared in the literature, and are therefore not included in this collection (interested readers

are referred to references given above).

I hope that this Special Issue of *Space Policy* will be a useful addition to the literature of space resource utilization, and stimulate discussion of how space resources may facilitate space science and exploration.

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Establishing lunar resource viability



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ABSTRACT

Recent research has highlighted the potential of lunar resources as an important element of space exploration but their viability has not been demonstrated. Establishing whether or not they can be considered in future plans is a multidisciplinary effort, requiring scientific expertise and delivering scientific results.

To this end various space agencies and private entities are looking to lunar resources, extracted and processed in situ, as a potentially game changing element in future space architectures, with the potential to increase scale and reduce cost. However, before any decisions can be made on the inclusion of resources in exploration roadmaps or future scenarios some big questions need to be answered about the viability of different resource deposits and the processes for extraction and utilisation. The missions and measurements that will be required to answer these questions, and which are being prepared by agencies and others, can only be performed through the engagement and support of the science community.

In answering questions about resources, data and knowledge will be generated that is of fundamental scientific importance. In supporting resource prospecting missions the science community will de facto generate new scientific knowledge. Science enables exploration and exploration enables science.

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1. Introduction

If humans are ever going to live and work on the Moon or on Mars in a long-term and sustainable way then dependency on resupply from Earth must be reduced to a minimum or removed completely. To achieve this requires that maximum use is made of any local resources that are available. However, the exploration roadmaps of agencies, consolidated in the Global Exploration Roadmap (GER) [1], do not assume any dependency on in-situ resources for currently conceived mission architectures. The absence of In-Situ Resource Utilisation (ISRU) as an assumption for future missions occurs primarily due to a lack of present confidence in its viability. The GER does however recognise that local resources will be an important element in the future. Until local resource utilisation becomes a part of the way missions are planned and executed, it is unlikely that long term sustainability of human exploration of the Solar System can be realised.

New knowledge, new capabilities and new technologies will be

required to make the transition to in-situ resource dependency, such that mission success is reliant on the availability and utilisation of resources extracted and processed locally. The Moon as the closest and most accessible destination for human exploration is likely to be the most feasible place to make this transition. Recent discoveries in lunar science and new technologies have changed the paradigm of what we know about potential resources on the Moon, offering new possibilities for resource utilisation to enable sustainable surface missions and develop in-situ resource dependency as an element in mission architectures and planning for missions to Mars.

2. The future of lunar exploration

In 2007 fourteen space agencies came together and agreed a common vision for robotic and human space exploration and a framework through which their activities could be coordinated. This vision and framework is recorded in The Global Exploration Strategy: The Framework for Coordination [2]. An outcome of this was the establishment of the International Space Exploration Coordination Group (ISECG) [3]; a voluntary, non-binding international coordination mechanism through which individual agencies

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may exchange information regarding interests, objectives, and plans in space exploration with the goal of strengthening both individual exploration programmes as well as the collective effort. The key product of this group is the Global Exploration Roadmap (GER) [1].

The GER represents a consolidated view of the exploration missions and plans of the ISECG participating agencies. It reflects a common long-range human exploration strategy that begins with the International Space Station and builds on this to expand human presence into the Solar System. The 'horizon goal' for the GER is sustainable human missions on the surface of Mars. The roadmap is updated periodically to reflect on-going developments in the participating agencies.

The most recent iteration of the GER was published in 2013. It focuses on the first steps in implementing this strategy: utilizing the ISS, continuing to expand the synergies between human and robotic missions and pursuing discovery driven missions in the lunar vicinity that evolve the capabilities and techniques needed to go further. The document recognises the importance of resources for future exploration and the need to characterise potential resources but explicitly defines mission scenarios that do not rely on lunar resources, stating that findings from robotic missions will inform future decisions regarding the promise of using lunar resources and their utilisation. It also states that human mission activities at the lunar surface, which it envisions from the end of the next decade, should advance knowledge that is related to the use of lunar resources and potentially provide the opportunity for advancing concepts related to use of local resources on Mars.

More recently, the Director General of the European Space Agency (ESA) has proposed the establishment of a Moon Village as a goal for the international community, following on from a human return to the lunar surface [4]. The Moon Village is envisaged, not as a discrete and predefined programme, but rather as an open architecture offering opportunities for different nations, and private sector entities, to contribute in an evolving and expanding partnership and a sustainable settlement. The Moon Village would offer multiple uses to multiple users; public and private sector, scientific and commercial. The utilisation of local resources would be an important and enabling element in the development of such a settlement and may also offer an opportunity for the commercial sector.

How then can early missions establish whether or not ISRU can be introduced as an enabling element in mission architectures?

3. The potential opportunities of lunar resources

Lunar resources have long been seen as an enabler for sustainable exploration and various schemes have been identified for their utilisation (e.g. Refs. [5] and [6]). These schemes all utilise regolith, the ground up fragments of lunar rocks that cover the lunar surface and which have resulted from billions of years of impacts by meteoroids (e.g. Ref. [7]). As well as mineral fragments regolith includes glass particles produced during impacts and particles called agglutinates, which are made up of smaller regolith particles fused together in a glassy matrix. Other particles in the regolith can be produced by volcanic events and are manifest as small glass beads (e.g. Ref. [7]). The sizes of regolith particles can vary from the nanometer scale [8] upwards, with mean particle sizes which are typically around 100 μm . The composition of the regolith is variable on both regional and local scales but any at any given lunar location is broadly related to the underlying geology, with relatively minor contributions from external sources, be they volcanic, ejecta from distant impacts or remnants of impactors themselves. The properties of regolith are also affected by the duration of its exposure at the lunar surface to impactors, cosmic radiation and solar wind

particles. This exposure results in a process called space weathering, with the extent of weathering often described as a regolith's maturity [7]. Incident solar wind particles become embedded in regolith and can be extracted as a gas by heating [9].

Regolith may be utilised as a feedstock for various processes which result in the production of materials for construction and manufacturing ([10] and [11]) or in chemical consumables for life support [4] or propellants [5].

In the case of consumables, attention has generally focussed on the production of oxygen which typically makes up around 40% of all lunar materials. Most proposed oxygen extraction processes employ a reducing agent (e.g. hydrogen or methane) which is introduced at high temperatures; typically several hundred to more than 1000 $^{\circ}\text{C}$ [12]. Oxidation processes (e.g. using fluorine) have also been proposed [13]. Extracted solar wind gasses have also been identified as possible resources [14].

A potential game changer in recent years, however, has been the confirmation that large scale deposits of water ice and other volatiles are present at the lunar poles [15]. Water is a consumable in and of itself, but is also a source of hydrogen and oxygen which can be used for life-support and propellant. While the presence of water ice has long been postulated at the lunar poles [16] it is only recently, following a number of successful missions, that a strong evidence base for its presence has been available.

The first strong evidence for water ice came from the Lunar Prospector Neutron Spectrometer, which detected an enhanced hydrogen abundance within a few tens of cm of the lunar surface across the polar regions when compared with lower latitudes [17]. This enhancement was consistent with a hypothesis that water ice was present, trapped in very cold areas where solar illumination was low or zero due to shading by surrounding topography. While the intrinsic resolution of the measurements was insufficient to sufficiently correlate hydrogen abundance with topography or the illumination conditions at the surface, statistical approaches were used to demonstrate that permanently shaded areas typically contained more hydrogen than the surrounding areas [18].

More recent data sets from various instruments on the Lunar Reconnaissance Orbiter (LRO) have significantly enhanced the evidence base. The DIVINER instrument demonstrated that surface temperature across the polar regions is sufficiently low as to enable preservation of water ice in the subsurface for geological timescales [19]. Furthermore, the temperatures in permanently shaded regions are some of the coldest in the Solar System, consistent with the thermal preservation of water ice at the surface. Measurements in the UV [20] by the Lyman-Alpha Mapping Project (LAMP) instrument, and by reflected laser pulses [21] produced by the Lunar Orbiter Laser Altimeter (LOLA), are consistent with variable degrees of surface frost in permanently shaded craters. Additional neutron measurements by Lunar Exploration Neutron Detector (LEND) have indicated a complex spatial distribution for bulk hydrogen [22]. Measurements by bistatic radar on LRO, and monostatic radar on the Indian Chandrayaan mission, indicate possible blocky ice material or ice layers at different locations ([23] and [24]).

Water has been definitively measured at only one location in the permanently shaded Cabeas crater in the South Polar Region by the L-CROSS impactor mission [25]. During this mission ejecta produced by the impact of a Centaur upper stage into the crater was observed using a suite of instruments in a shepherding spacecraft, by LRO and from Earth. These measurements showed the presence at water at this location of approximately 5% within 2–3 m of the surface, assuming that the water content of the plume was consistent with that in the surface.

Lunar ice and other cold trapped volatiles at the lunar poles present a favourable first target as a resource. If present in sufficient quantities then, conceptually at least, the extraction of water from

the regolith through heating and the generation of products from that water (e.g. hydrogen and oxygen by electrolysis) is fairly straightforward. However, the steps to be taken to achieve this are not yet established and the challenges are not yet fully understood.

Whilst knowledge of polar volatiles, and water in particular, has been advanced tremendously in recent years, our knowledge remains insufficient to consider it as a viable resource. Major unknowns remain regarding the composition, abundance and distribution [26] as well as extractability of water ice and other volatiles at the lunar poles. A first step towards their utilisation must be to characterise the deposits and address these unknowns. This is a job for the first prospecting missions.

4. Steps to utilisation

Whether the resource in question is cold trapped polar ice or something else, there are a number of steps that need to be taken to establish their viability as a source of resources, that the capability exists to extract and store those resources, and that their utilisation will bring benefits over and above resupply from Earth. These steps can be summarised as:

- Find and characterise the resource deposits
- Validate the required technologies
- Demonstrate extraction and utilisation

Each potential resource and deposit will have its own set of unknowns and unique challenges. These need to be addressed in a stepwise manner through a process roughly along the lines set out below.

4.1. Characterising the deposit

The first step in establishing the viability of a resource is to find where it is located and then to characterise the extent of a deposit and the physical and chemical properties of the ore or bulk material from which it is to be extracted. While comprehensive measurements have been made of the physical and chemical properties of lunar regolith in the past, and samples of lunar regolith are available from the Apollo missions, these samples may have limited direct applicability to previously unexplored landing sites such as those in the polar regions.

Taking polar regolith as an example there are a great number of unknowns remaining. Many of these unknowns are well described in a recent white paper [26] by the Friends of Lunar Volatiles. While we now know that water ice and other volatiles are present in the lunar polar regions the detailed distribution of this is unknown. The single point measurement of L-CROSS gives a good indication of what to expect at that location but represents a bulk concentration at a site which was selected as the most favourable location to search for water ice based on orbital data sets. The combination of orbital data sets show the distribution to be complex and non-intuitive, with some shaded regions rich in volatiles while others are not, and with some showing expressions of possible surface volatiles and others not. Some data sets indicate water outside of permanently shaded regions. This distribution may be related to the sources that delivered these volatiles to the lunar surface and the exposure and illumination history of the Moon. For example true polar wander may have moved the location of the lunar poles over time and led to a change in the areas that are permanently shaded or able to preserve water ice [27]. This complexity in distribution contrasts with that found on Mercury, where water ice deposits are clearly observed at permanently shaded craters in polar regions [28] at exactly the locations where they had been predicted based on illumination and surface temperatures.

The physical properties of these deposits are also unknown. Some experiments on regolith simulants containing water ice in different quantities have been performed with differing results, some of which indicate that in extreme cases water ice at saturation may result in high cohesive strength. Measurements of thermal properties from orbit and observations of the L-CROSS impact event however seem to indicate that polar regoliths in the coldest regions may be extremely soft and unconsolidated [29].

At present we cannot determine whether water ice is in permanently shaded areas only or more broadly distributed. We do not know which shaded regions contain water and which may not. We do not know the depth to which these deposits may be found. We do not know the concentration or abundance of volatiles in these deposits or how this varies with depth. We do not know the composition of the volatiles in these deposits or from whence they came. We do not know the material properties of the regolith containing this material and we do not know the thermal and illumination environments in which they are found.

Any effort to establish lunar polar volatiles as a resource must first characterise the deposits on both local (within tens of km) and regional (from 0° to approximately 75° latitude North and South) scales. This can only be accomplished by missions to the surface, examples of which are outlined in later sections.

An important aspect of this characterisation phase is that pursuing it requires a partnership between the science community and the agencies and private sector entities that may choose to extract the resources. All of the information that exists today has been generated as a result of the efforts of the science community. It is here that the expertise to perform this work resides and it is these skills that must be called upon to accomplish the task.

In doing so, fundamental research will also benefit. These polar deposits are repositories of Solar System history. They may be derived from impacting asteroids and comets or from solar wind, incident over billions of years. They may contain complex organic molecules from their original sources or generated in situ through exposure to the radiation environment [30] and through impact processes [31]. Missions providing access to and measurement of these materials will yield a wealth of new scientific knowledge relevant to the processes and history of volatiles in the inner Solar System and the sources of life enabling chemistry.

4.2. Validating the required technologies

Having defined the extent and properties of a given deposit the specific challenges associated with extracting and processing the resource can be identified. These challenges may be associated with the environment in which those resources are located (e.g. operations in permanent darkness and low temperatures at the lunar poles); the mechanical properties of the feedstock to be extracted (e.g. water ice-bearing consolidated regolith); the process by which the feedstock is to be converted into a resource (e.g. water extraction and electrolysis or thermochemical reduction of regolith) or the process by which a resource is stored, preserved and later delivered for use. Each of these steps poses its own challenges and may require new developments, which may need to be tailored to the specific deposit or resource.

Having developed these systems and technologies they will need to be validated and verified in a representative environment. For many of these technologies the environment can be simulated in terrestrial laboratories and analogue environments. However, for those technologies which must interact directly with the lunar regolith (e.g. excavating tools and chemical reactors), or those that rely on gravity to play a part, will almost certainly require demonstration to be performed in the lunar environment. This too can be performed by robotic missions and early human missions.

Demonstrations could be performed at technology or system level and could potentially be combined with an end to end system demonstration.

4.3. Demonstrating extraction and utilisation

A final step is to demonstrate the end to end process associated with a resource using what may be termed as a pilot plant. In this scenario a feedstock must be extracted from its environment. The feedstock must then be processed and converted into a usable resource. The resource must then be made available and utilised directly or stored for future use. Waste products must also be handled appropriately.

Ultimately the resource should be utilised as a non-essential part of a mission. For example water generated from polar ice could be transferred for human consumption or oxygen could be transferred for use in a habitat. In performing this final step the end to end process has been verified and demonstrated to a point that future missions can employ a degree of confidence in the resource and plans can be made on the basis that it provides a viable and credible alternative to terrestrial supplies.

Considering such a pilot plant as the vital step to demonstrate the viability of ISRU, and permit agencies and others to consider it as a key enabling element of exploration plans, also focuses attention on specific questions: where should such a pilot plant be located, what type of feedstock(s) should it use, which type of environment(s) must it operate in, etc. All of these questions provide very clear requirements for near term precursor missions, and are also critically linked with the longer term utilisation scenario of these resources in exploration.

5. Characterising polar volatile deposits with robotic precursor missions

In the case of lunar polar volatiles there is much work to be done to characterise their resource potential. An international effort to develop a communal understanding of the knowledge gaps and technical challenges associated with lunar polar volatiles, and to enable the coordination of technology development and mission planning in this area, is being conducted by ISECG. This effort, performed in advance of the next iteration of the GER is facilitating inter-agency discussions on the subject and is extending this dialogue to the international science community, the private sector and others with an interests and expertise in the area [32]. Significant work is on-going internationally in this domain, with key examples being NASA's Resource Prospector and the Russian led luna-27 mission, which is planned for a landing in the early 2020s at a high latitude location. Luna-27 will carry ESA's PROSPECT system, which will drill into the sub surface, extract samples of potentially water ice bearing regolith from depth and extract and analyse the potential resources in these samples.

In order to properly characterise the deposits at the lunar poles on both regional and local scales surface measurements are required, which may be performed by different mission types with different strengths. Some of these are discussed below.

5.1. Comprehensive single point measurements

Landers without mobility can make measurements at single point locations. Of primary interest in this case are the composition, abundance and vertical distribution of water ice at the given location. These measurements can provide ground truth for orbital measurements, which in the case of epithermal neutrons provide bulk measurements of hydrogen abundance within approximately 1 m of the surface and within an area on the scale of tens of km across.

In favour of this approach is the relative simplicity of accessing a single point without the need for mobility. There are however some limitations to the comprehensiveness that such missions can provide. Given the uncertainty in the lateral distribution of volatiles on a local scale there can be no guarantee that a landing site will be well suited to volatile investigations. While it seems likely that a general enhancement will be observed across the polar regions, such that detection and chemical characterisation may be performed, any measurements of distribution and abundance made at a single location cannot be assumed to be valid more generally. An additional issue arises due to possible contamination from the propulsion system of the lander and outgassing. Some of these volatile contaminants coincide with the chemistry of interest for measurement and so there is a risk that measurement can be compromised.

A possible mitigation approach in both cases is to emphasise the accurate and precise measurement of isotopes. The ratios of different isotopes of different elements within chemicals of interest provide a marker for the origins of those chemicals and the processes that have emplaced them. For example the ratio of deuterium to hydrogen (D/H) in water is strongly dependant on the source. Solar wind hydrogen contains very little deuterium and so water derived from solar wind delivered hydrogen can be identified by a D/H ratio approaching zero [33]. Water in comets, asteroids, the lunar interior and terrestrial reservoirs all have indicative, although not always different, D/H ratios ([33–35]). Other volatile chemicals, in particular carbon, nitrogen, oxygen and noble gases can also be used as markers ([36–38]). In addition, migratory and emplacement processes taking place will further fractionate isotopic measurements, such that measurements of isotope systematics can inform models of migratory processes, allowing local measurements to be extrapolated to a more general scenario. Spallation reactions taking place when regolith particles interact with energetic cosmic radiation will lead to the formation of additional isotopic species which can be identified, yielding for example the length of time a that a sample extracted from depth has spent close to the surface in the past. Isotopic markers may also be used to identify and track contaminants introduced by the lander.

5.1.1. PROSPECT

The Package for Resource Observation and in-Situ Prospecting for Exploration Commercial Exploitation and Transportation (PROSPECT) is a system in development by ESA to evaluate resource potential at the Moon's surface. It can be deployed on a fixed lander or a mobile platform, and its capabilities can be tailored to suit the characterisation needs of a given deposit. The first flight for PROSPECT is planned on the Russian Luna-27 mission, which will target the lunar South Polar Region.

PROSPECT includes two elements; a drill which will extract and deliver regolith samples from depths of up to and potentially more than 1 m, and a chemical laboratory which will extract potential resources from the regolith feedstock as gas and analyse these released gases.

The ProSEED drill (PROSPECT Sample Excavation and Extraction Device) is derived from heritage developed in planetary drilling through the Exomars and Rosetta-Philae missions. ProSEED must penetrate a material whose properties are unknown. In the polar region the regolith could have a very low water abundance, that does not affect the mechanical properties, resulting in a material akin to that experienced by Apollo. Alternatively the material properties may be radically different, with water ice fusing the regolith particles into a consolidated ice concrete. The drill must be able to penetrate and sample this material, without inhibition by rock inclusions and whilst preserving any contained ice. In the high

vacuum of the lunar environment ice extracted from the subsurface can be lost through sublimation extremely rapidly, even at very low temperatures [39].

Samples from the drill can then be passed on to the Russian sample handing system, in the case of Luna-27, and to the ProSPA (PROSPECT Sample Processing and Analysis) system. ProSPA is derived from the Lunar Volatile Resource Analysis Package (LVRAP) concept described in Ref. [40] and builds on the technologies developed for Ptolemy on Rosetta and GAP on Beagle 2. Upon receiving the sample ProSPA seals it in a reactor and begins to heat it. Samples are expected to be delivered at temperatures of around -150°C . As temperature is raised water vapour and other gasses (e.g. H_2 , N_2 , CO_2 , CO) derived from the solar wind, meteoritic, cosmogenic and indigenous sources. Oxygen introduced to the samples enables combustion. When high enough temperatures are achieved reactant gasses can be introduced to the sample to investigate oxygen extraction processes from regolith, such as reduction in hydrogen or methane or oxidation with fluorine.

Gases released in these processes will then undergo a chemical analysis using a mass spectrometer to determine the composition of the extracted gases and their abundance. Gases will then be introduced to a gas processing system where they are separated and chemically altered to allow precise and accurate elemental isotopic analysis to be performed using a magnetic sector mass spectrometer. The goal is to generate isotopic measurements of a quality comparable to terrestrial laboratories.

If water ice is present in the samples then PROSPECT will demonstrate its extraction and determine its abundance, origins and emplacement processes. Other chemical species in the ice will also be identified and analysed. A comprehensive isotopic analysis determines origins and processes to inform models of likely abundance and distribution, even from a stationary platform. Isotopes can also be used to identify and account for contamination from terrestrial sources and the lander.

5.1.2. Sample return

If in-situ measurements confirm the presence of scientifically interesting chemistry in the polar regions a case can be made for sample return to follow. A Lunar Polar Sample Return mission is currently being studied by ESA as a possible future collaboration with Russia. The mission scenarios under discussion are static missions without surface mobility and as such can be considered as follow on to the measurements performed with a static in-situ measurement package such as PROSPECT on Luna-27.

Sample return missions offer the best opportunity for comprehensive measurements to be made. Retuned samples can be analysed in terrestrial laboratories to an extent that is not possible in-situ. They can also be curated for future analysis by terrestrial analytical instruments and protocols as yet not conceived. Thus sample return provides the most scientifically rich return and a legacy for the future. This legacy is exemplified by the on-going scientific return from samples returned by the Apollo missions.

The characterisation of resource deposits does not fundamentally require chemical analysis of returned samples as a high priority, focussing instead on broad composition, abundance and distribution on a local or regional baseline, which can be performed in-situ. Measurements of returned samples will however provide a useful input to such assessments, in particular if they are performed in synergy with surface measurements over a broader baseline.

It may also be that sample return missions offer a feasible way to access and analyse the interior of large permanently shaded regions; such the Cabeus, Shoemaker or Peary craters, which are favoured locations for extensive volatile deposits. The lack of solar energy provision in these areas imposes severe restrictions on in-situ operations, imposing extreme limits on what could

conceivably be achieved with an in-situ measurement campaign. Sample return missions need operate in these locations for very limited periods while samples are extracted and contained. As such the need for solar power at the surface may be removed.

5.2. Regionally distributed point measurements with small missions

Small platforms with limited analytical capabilities may also have an important role to play in the characterisation of polar volatiles by providing multiple data points across the polar regions. While any ground truth on the abundance of polar volatiles would be of benefit it is important to observe the variation and diversity of volatile abundance and distribution at different locations, with different surface environments, different temperature and solar exposure characteristics and different apparent hydrogen concentrations when viewed from orbit.

An example of such a platform could be a penetrator [41] with a minimal payload focussing on detection of water, perhaps by mass spectroscopy or using a neutron spectrometer to identify local hydrogen (assuming these instruments can survive the required high G loads of impact). Care would need to be taken to interpret the effects of the impact of a penetrator on the environment to be measured.

A number of these small platforms deployed across the polar regions to different locations could provide insight in to the regional distribution and homogeneity of deposits.

5.3. Local deposit characterisation with mobile platforms

Current maps of hydrogen distribution from orbit provide the best current estimate of water distribution across the polar regions but exist only with surface resolutions of which can be tens of km. Within these surface areas there is neither ground truth to confirm how this signature should be interpreted in terms of content and distribution, nor any measurements to indicate the variations within different locations, environments or terrains. A mobile platform with a range comparable with the size of a single pixel can map out the distribution during such a traverse. The rover would need to access a variety of terrains with different properties and to perform measurements throughout the traverse. A payload might include a neutron spectrometer to determine bulk hydrogen concentration up to around 1m beneath the surface and a ground penetrating radar (e.g. Ref. [42]) to identify sub surface structure to a few meters, a near infrared spectrometer (e.g. Ref. [43]) could measure water and chemical content at the surface during the traverse or monitor the fresh regolith disturbed by rover tracks during the traverse. At designated way points of interest a drill derived from PROSPECT could be used to extract subsurface samples for analysis by a ProSPA-derived chemical analyser. While isotope systematics for this system might be of high scientific interest the introduction of mobility reduces the fundamental need for such a capability for purposes of resource characterisation. A reduced capability, focussing on chemical characterisation, may be sufficient and optimised for the rover mass and needs. These measurements would provide sub-surface ground-truthing to support interpretation of the data sets generated throughout the traverse.

6. Conclusions

Lunar resources have long been discussed but cannot yet be considered as viable in exploration architectures. To get to this point requires that resources are fully characterised in-situ and then demonstrated to be utilisable.

Of all potential resources on the Moon lunar polar ice is perhaps

the most easily exploitable since, if present in sufficient quantities in accessible locations, its extraction and processing could be straightforward, at least conceptually.

Determining whether or not polar water ice is accessible in sufficient quantities and concentrations at accessible locations however requires a comprehensive characterisation effort, at the surface, and on a regional and local scale. Different types of platforms of different scales and complexities can all play a part in addressing these questions.

Achieving this will require a comprehensive involvement by the scientific community. The measurements and activities undertaken will also result in an important scientific return.

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Viewpoint

The long-term scientific benefits of a space economy



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ABSTRACT

Utilisation of the material and energy resources of the Solar System will be essential for the development of a sustainable space economy and associated infrastructure. Science will be a major beneficiary of a space economy, even if its major elements (e.g. space tourism, resource extraction activities on the Moon or asteroids, and large-scale in-space construction capabilities) are not developed with science primarily in mind. Examples of scientific activities that would be facilitated by the development of space infrastructure include the construction of large space telescopes, ambitious space missions (including human missions) to the outer Solar System, and the establishment of scientific research stations on the Moon and Mars (and perhaps elsewhere). In the more distant future, an important scientific application of a well-developed space infrastructure may be the construction of interstellar space probes for the exploration of planets around nearby stars.

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1. Introduction

There is no doubt that science has been a major beneficiary of the space age. Ever since the discovery of Earth's radiation belts by only the second and third artificial Earth satellites ever launched (i.e. Sputnik 2 in 1957 and Explorer-1 the following year), scientific knowledge has poured down to Earth from spacecraft operating throughout the Solar System. Major scientific disciplines like astrophysics and planetary science have undergone paradigm-changing revolutions as a consequence, in the former case by the ability to conduct astronomical observations above the obscuring effects of Earth's atmosphere, and in the latter by being able to make *in situ* measurements of planets and other solar system bodies that previously could only be observed remotely using telescopes. In the second decade of the twenty-first century, it is sobering to contemplate just how limited our knowledge of the Universe would still be had the space age not begun when it did.

It is clear that science still has much to gain from continued access to space, but already there are concerns that access on the scale required to maintain the current rate of scientific discovery, let alone to increase it, may not be achievable with current funding models [1,2]. The main concern is that, as space missions become more complex, their cost grows faster than do scientific budgets, or

even the Gross National Products of participating countries. As pointed out by Martin Elvis elsewhere in this volume [2], ultimately this must result in space science hitting a 'funding wall' which will curtail future growth, and thus limit future scientific discoveries. One way, and perhaps the only way, to avoid this funding limit will be to 'piggyback' space science and exploration on the activities of a future space-based economy developed largely for commercial purposes [e.g. [1–4]].

2. Space resources

To be sustainable, any future space-based economy, whether built around commercial satellite operations, space tourism, mining the Moon and asteroids, or any combination of these, will increasingly rely on utilising the energy and material resources of the solar system [e.g. [4–9]]. This is simply a consequence of the energy cost of lifting the required materials out of Earth's gravity well: if materials are to be used in space it will always be more economically attractive to source them in space. However, the process will be gradual and iterative, because many of these space resources will only be useful once an infrastructure exists to access and extract them.

There are at least four, mutually reinforcing, ways in which the scientific exploration of space will benefit from the development of a space economy built around the utilisation of extraterrestrial resources.

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2.1. Economic benefits of using space resources in space to build, provision, and maintain scientific instruments and outposts

It has long been recognized that future space exploration activities would benefit from utilising extraterrestrial resources wherever possible (an application known as *In Situ Resource Utilisation*, or ISRU), as this would avoid having to lift them out of Earth's gravity [4,7,10–12]. For example, scientific outposts on the Moon and Mars would benefit from using indigenous water resources (e.g. for drinking, personal hygiene, and as a source of both hydrogen and oxygen). Similarly, future space stations, satellites (including, in the present context, the next generation of large space telescopes), and space probes to the outer solar system would benefit if the hydrogen and oxygen needed for rocket fuel (as well as oxygen to breathe if human crews are involved) could be sourced in space (e.g. from the lunar poles [8,13] or from hydrated asteroids [14,15]). For such applications, it is not the intrinsic value of the resources themselves that are scientifically enabling but the economic savings resulting from reduced launch masses from Earth. As Drmola and Mareš [16] succinctly put the case for ISRU:

“It is not the prospect of procuring something we covet here on the surface of the Earth that makes this venture attractive, but rather the idea of not having to wage an expensive battle with Earth's gravity each time we want to make use of something as mundane as water in space.”

2.2. Scientific discoveries made in the course of resource prospecting/extraction

Companies engaged in prospecting for exploitable raw materials elsewhere in the solar system will inevitably rely on the knowledge and technical expertise of the planetary science community. However, by the same token, planetary science will learn much from this prospecting activity owing to improved access to a wider range solar system bodies (e.g. comets, asteroids, and lunar and planetary surfaces) than would otherwise occur (see the discussion summarised in Ref. [4]). This will greatly increase opportunities for making *in situ* measurements, and for returning a diverse range of samples to Earth for analysis, all of which will increase our understanding of the origin and evolution of the Solar System. There is a clear analogy here with the symbiotic relationship which exists between the geological sciences and the resource extraction industries on Earth – the latter needs the expertise of the former in order to locate economically exploitable resources, but the former also benefits from discoveries made, and techniques developed, by the latter. The same dynamic is sure to play out in space as the economic development of the solar system proceeds.

2.3. Leveraging the growth of the space economy to pay for space science

Ultimately the ‘New Space’ entrepreneurs behind the commercialisation of space activities are seeking to make a profit, and the bigger the space economy becomes the larger will be the profits generated. Some of these profits will doubtless be re-invested in further space exploration and development, leading to increased opportunities for scientific discovery as outlined in Section 2.2 above. However, it will presumably also be the case that companies profiting from commercial space activities will be subject to taxation by some Earth-bound jurisdiction (whether this be national governments or some as yet to be implemented international authority [e.g. [5,17–19]]). Thus, by instituting creative regulatory mechanisms, it may be possible to arrange for some of the profits

generated in space to be invested in government-led ‘blue skies’ space science activities unrelated to the commercial activities themselves. Financing, or part financing, of the next generation of large space telescopes, or human missions to Mars, might be examples. In any case, it seems clear that once space activities begin to pay for themselves, and clearly contribute to the global economy rather than being (or being perceived to be) a drain upon it, then more opportunities to finance purely scientific endeavours in space are likely to arise.

2.4. Utilisation of the infrastructure developed to support commercial space activities

Last, but not least, space science and exploration will benefit from the *infrastructure* developed to support a space economy. Consistent with its usual definition, by space infrastructure I mean all the transportation capabilities, habitats, trained personnel, and other capabilities that will facilitate wide-ranging human operations in the space environment (Fig. 1). It is inherent in the nature of infrastructure that it can support multiple activities; for example, a spacecraft designed to transport people could carry tourists, asteroid miners, and, in the present context, scientists all at the same time.

As I have noted elsewhere [20], there is a clear analogy here with the multiple uses of civil aviation infrastructure on Earth. For example, astronomers, geologists and zoologists invariably make use of an extensive commercial aviation infrastructure (which, of course, is largely underpinned by the tourism industry) in order to visit their observatories and field localities, without having to design, build, and operate commercial airliners. This is not a trivial point: because scientific budgets would be wholly inadequate to develop such an infrastructure, if it had not been created for other reasons then a lot of scientific activity on Earth simply could not occur. Future scientists operating on the Moon, Mars and asteroids (and indeed throughout the solar system) would similarly benefit from a commercial interplanetary transportation infrastructure. Similar comparisons can be made with other aspects of infrastructure. For example, just as telescope construction on Earth relies on the availability of a commercial construction industry, so future large space telescopes will be enabled by the existence of a space-based equivalent, even if most of its business case relies on

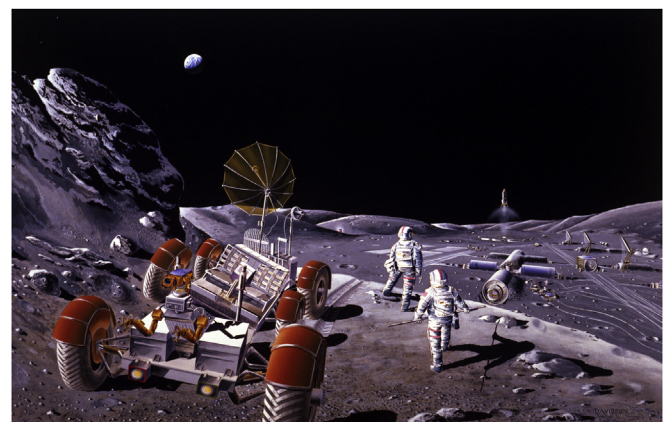


Fig. 1. Infrastructure on the Moon. This artist's drawing of future lunar exploration includes multiple infrastructural elements, including habitats, local transportation (rover), interplanetary transportation (rocket), and trained personnel (astronauts). Such an infrastructure could support multiple activities, including resource prospecting, tourism, and, in the present context, scientific research. Sustainable operation of such an infrastructure will require the use of *in situ* resources and will enable planetary exploration on a scale that will not otherwise be possible (NASA).

commercial activities, such as building orbital hotels or satellite solar power stations, quite unrelated to science.

3. Thinking further ahead

In the above, I have alluded to relatively near-term (say within the next fifty years) examples of scientific benefits likely to result from the gradual development of a space economy and associated infrastructure. These include the construction of large space telescopes, in depth studies of a wide range of asteroids, cheaper and more capable robotic missions to the outer planets, and the establishment of scientific research stations on the Moon and, in due course, Mars. However, once a space economy is established it may be expected to grow exponentially, and in time this will enable still more ambitious feats of scientific exploration.

One such longer term opportunity might be human exploration missions to the giant planets and their moons. Currently, it is taken for granted that missions to the outer solar system will, of necessity, be robotic, mainly owing to the very long travel times required (with attendant consequences for life support consumables, radiation shielding, and microgravity mitigation), and the very hazardous radiation environments in the vicinity of the giant planets. However, if it were ever possible to send human explorers to, say, Europa or Titan, then all the advantages that human explorers will have over robots when exploring the Moon or Mars (i.e. greater versatility, on-the-spot decision making, intelligent sample collection, maintenance and deployment of complex equipment, greater opportunities for serendipitous discovery, etc. [21–23]) would apply to those bodies as well. Given the scientific importance of the icy worlds of the outer solar system, not least from an astrobiological perspective [24,25], the scientific rewards from being able to send people there (or at least to their vicinity so as to permit real-time telerobotic operations [26]) could be significant.

In spite of the well-recognized difficulties, studies of human missions to the outer solar system have been conducted [e.g. [27]] and, although technically demanding, are certainly not impossible. Indeed, most of the seemingly insurmountable difficulties arise from the large spacecraft mass that would be needed for any human mission to the outer solar system. Such missions are likely to require launch masses of several thousand tonnes, driven largely by the mass of the propulsion system (presumably nuclear of some kind) needed to reduce transit times to acceptable levels (i.e. months to a small number of years), the mass of life support consumables required, and the mass of radiation shielding [27]. However, while probably unrealistic if launched directly from Earth, the economics of such a mission would be completely transformed in the context of a space economy where the spacecraft could be assembled and launched, and many of the consumables sourced, from low gravity environments in the inner solar system. It will of course take time (surely many decades) for a solar system economy to ‘bootstrap’ itself up to a level at which it could realistically support such activities, but when it is able to do so the scientific exploration of the outer solar system is likely to be a major beneficiary.

In the more distant future, an important scientific benefit of a well-developed space infrastructure may be the construction of interstellar space probes for the exploration of planets around nearby stars. The history of planetary exploration clearly shows that *in situ* investigations by space probes are required if we are to learn about the interior structures, geological evolution, and possible habitability of the planets in our own solar system, and so it seems clear that spacecraft will eventually be needed for the investigation of other planetary systems as well [28]. For example, if future astronomical observations from the solar system (perhaps using large space telescopes themselves built and paid for using space resources) find evidence suggesting that life might exist on a

planet orbiting a nearby star, *in situ* measurements will probably be required to get definitive proof of its existence and to learn more about its underlying biochemistry, ecology, and evolutionary history. This in turn will eventually require transporting sophisticated scientific instruments across interstellar space.

However, the scale of such an undertaking should not be underestimated. Although very low-mass laser-pushed nano-craft, such as are being considered by Project Starshot [29], could conceivably be launched directly from Earth, the scientific capabilities of such small payloads will surely be very limited. In order to get a scientifically useful payload (which, even allowing for future progress in miniaturisation, will surely need to have a mass of at least several tonnes, and possibly very much more if detailed investigations are to be made [30]) to even the nearest stars (all several light-years away) within scientifically useful timescales (say ≤ 100 years) then spacecraft velocities of order 10% of the speed of light will be required. Of course, this far exceeds present capabilities and will likely require vehicles of such a size, with such highly energetic (and thus potentially dangerous) propulsion systems [e.g. [31–33]], that their construction and launch will surely have to take place in space. The potential long-term scientific benefits of an interstellar spacefaring capability are hard to exaggerate, but it seems certain that it is a capability that will only become possible in the context of a well-developed space economy with access to the material and energy resources of our own solar system [5,31].

4. Conclusions

The solar system is rich in energy and material resources which could potentially support a vibrant future space economy. Although many aspects of this economic activity will probably be pursued for purely commercial reasons (e.g. space tourism, and the mining of the Moon and asteroids for economically valuable materials), science will nevertheless be a major beneficiary. Indeed, science will benefit from all stages in the ‘bootstrapping’ of a space economy, from initial prospecting activities on the Moon and asteroids, through to the utilisation of the resulting resources to expand space activities. In particular, science will benefit from the *infrastructure* developed to support a space economy, which will help facilitate the construction of large space telescopes, the establishment of scientific research stations on the Moon and Mars (and perhaps elsewhere), and the mounting of ambitious space missions (including human missions) to the outer Solar System. In the more distant future, an important scientific benefit of a well-developed space infrastructure may be the construction of interstellar space probes for the exploration of planets around nearby stars.

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Near Earth asteroid resource utilisation for large in-orbit reflectors



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ABSTRACT

The resources offered by the family of near Earth asteroids could provide bulk materials to support future space science ventures, both crewed missions and space-based astronomy. Using low-energy transfer trajectories small near Earth asteroids could be captured directly, or their material resources returned to Earth orbit or the Lagrange points. With novel fabrication methods, such as additive layer manufacturing, large-scale space structures including optical and radio telescopes could in principle be assembled from such resources. Indeed, with bulk materials readily available, very large numbers of structures could be fabricated in-situ for interferometry applications.

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1. Introduction

The inherent cost of large science missions (whether robotic or crewed exploration) is in part due to the cost of lifting material from the bottom of the Earth's deep gravity well. However, emerging technologies offer the possibility of sourcing material from in-situ resources, including the Moon and the family of near Earth asteroids [1]. Such resources include water from C-type asteroids, either for logistic support or to be electrolytically cracked into hydrogen and oxygen for propellant. Metals from M-type asteroids offer a wider range of in-situ resources for manufacturing.

While the Moon provides an important potential resource [2], it also requires material to be lifted from its own gravity well, while asteroid resources are arguably more accessible. This can be seen by estimating the near Earth asteroid resources available with an energy investment equivalent to lunar escape speed. For example, with a Δv investment of 2.73 km s^{-1} (lunar escape speed) approximately 10^{13} kg of near Earth asteroid material is in principle available [3]. Importantly, while lunar escape speed represents the minimum energy investment required to lift material from the Moon to escape, asteroid resources can be accessed across a spectrum of energy investments, starting from a relatively low threshold. With a Δv investment of only 100 m s^{-1} approximately 10^{10} kg of asteroid material is in principle available, given the orbit and size distribution of the near Earth asteroid population [3]. Indeed the most easily accessible known target (2006 RH120, with

a diameter of a few meters) can be captured with a Δv investment of order 60 m s^{-1} [4].

While near Earth asteroid resources are often seen as enabling future human space ventures, they could also provide exciting new opportunities for space science; for example, by providing bulk material for large-scale reflectors for optical or radio astronomy. Combined with new technologies, such as additive layer manufacturing, the convergence of in-situ resources and new fabrication methods could enable entirely new ways of delivering space science in future [5]. Moreover, with additive layer manufacturing, multiple reflectors could be fabricated at low marginal cost to enable interferometry with very large numbers of elements. In-situ resources from near Earth asteroids would provide bulk material for reflectors, while specialised subsystems, such as instruments and detectors, would be launched from Earth.

In this Viewpoint some recent work on near Earth asteroid capture, material processing and the deployment of large-scale reflectors will be synthesised and discussed. Possibilities for the fabrication of multiple large-scale reflectors for space-based astronomy and interferometry will then be speculated upon.

2. Asteroid capture

While the family of near Earth asteroids represent a vast potential wealth of material, the accessibility of that material for space science or other purposes is constrained by orbital dynamics. While some target objects have orbital elements similar to those of the Earth, others move along eccentric and/or high inclination orbits which require significant energy to reach and return from.

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Recent work has shown that the stable invariant manifolds of the L_1 and L_2 Lagrange points of the Sun–Earth system could be used as efficient routes to capture small near Earth asteroids, or return material processed from them [4,6]. The stable manifolds represent families of trajectories which naturally wind onto periodic orbits at the L_1 or L_2 Lagrange points, either in-plane Lyapunov orbits or North/South halo orbits.

First, a spacecraft with an efficient, high specific impulse propulsion system (likely solar electric propulsion) would rendezvous with a target body and mechanically grapple the asteroid. A burn from the low thrust propulsion system would then push the asteroid onto a ballistic trajectory which intersects the desired stable invariant manifold. A subsequent burn would then push the asteroid onto the manifold itself, after which it would naturally wind onto a periodic orbit about either the L_1 or L_2 Lagrange point. While the co-linear Lagrange points are unstable, active control of captured bodies at such locations appears possible [7], while the Lagrange points themselves represent potential staging posts for future human space activities, or locations for space-based astronomy [8]. Returning material directly to the L_1 or L_2 Lagrange points could therefore provide resources to support such ventures.

In addition to Lagrange point capture, recent work has also shown that low-energy capture is possible using so-called Kolmogorov–Arnold–Moser (KAM) tori [9]. In this strategy an asteroid moving on an initially chaotic orbit in the Sun–Earth system is manoeuvred, again likely using an efficient, high specific impulse solar electric propulsion system. The manoeuvre pushes the asteroid inside a so-called KAM torus which traps it on a periodic orbit about the Earth. Remarkably, the asteroid still has sufficient energy to escape, but doesn't (the zero velocity surfaces at the L_1 and/or L_2 Lagrange points remain open). In principle the asteroid can escape through so-called Arnold diffusion, but the diffusion timescale is so long that the asteroid remains trapped for practical engineering purposes [9].

Using insights into orbital dynamics it appears that capturing or returning material from near Earth asteroids could be efficiently achieved, although the total time integrated impulse required is still large. Moreover, some asteroids are in relatively easily accessible orbits representing the lowest costs targets, so-called Easily Retrievable Objects (EROS), with a capture Δv of less than 500 ms^{-1} [4]. While the near Earth asteroid resource is vast, it will clearly be harvested in the most efficient manner, leading to competition for the most easily accessible resources.

3. Material sorting

Aside from capturing or returning material from near Earth asteroids, another key challenge is material sorting. This is particularly acute since most terrestrial mining processes often rely on gravity to sort ground materials. Clearly, direct gravitational sorting is not feasible in the weak gravity of near Earth asteroids. However, material can in principle be sorted using light pressure as an effective sieve to sort grains by density [10]. In this strategy grains of material are lofted from the asteroid surface with light pressure perturbing the lowest density grains more strongly than dense metallic grains, since the acceleration due to light pressure scales with area-to-mass ratio. As the lofted grains slowly sink back to the asteroid surface lighter grains such as olivine (density of order 3.5 g cm^{-3}) will have been perturbed more strongly than dense metallic Fe–Ni grains (density of order 7.5 g cm^{-3}). In this manner bulk sorting of material could be achieved. Practically, a rover could move across the asteroid surface gathering and lofting material while other rovers move synchronously to collect separated grains. The entire group of rovers can move across the asteroid surface at a suitable speed to ensure that the Sun–asteroid–grain geometry is

optimised to maximise the relative displacement of dense grains and lighter grains [10].

4. Large gossamer reflectors

Assuming a source of metallic grains is available from processed near Earth asteroid resources, thin film metallic reflectors can in principle be fabricated. Vapour deposition of aluminium from metallic powder feedstock has been considered for the fabrication of large solar sails [11]. The vapour is deposited onto a cold roller and then the thin metallic film separated to be seamed to form larger structures. Modern additive manufacturing technology can also be envisaged to fabricate large thin films with a load bearing structure manufactured directly on top of the film [5].

For a parabolic collector to be used for space-based optical or radio astronomy the parabolic form could be generated via a rigid load-bearing structure. However, recent work has shown that light pressure can be used to deform a large slack membrane into a parabolic shape [12]. A disk membrane supported by an outer hoop structure is envisaged. It can be shown that for a membrane of uniform reflectivity the deformed shape is not parabolic. But requiring a parabolic form a priori, the required surface reflectivity profile required to generate such a shape via light pressure can be determined. The required azimuthally symmetric variation in reflectivity from the centre to the edge of the disk can in principle be manufactured during fabrication of the reflector, while active control appears possible using patches of electrochromic coatings. For example, a 100 m radius spinning disk with a slack length of order 105% of the disk radius can generate a parabola with a focal length of the same order as the disk radius itself, where the disk is perfectly reflective at its centre and absorbing at its edge [12]. In principle then, ultra-large but lightweight parabolic reflectors could be fabricated from in-situ resources. While requirements on the accuracy of the surface profile of optical reflectors are clearly demanding, radio frequency applications are less stringent.

For space-based astronomy the axis of the reflector clearly needs to be pointed in arbitrary directions. However, using light pressure to deform the membrane into a parabolic shape implies that the reflector needs to be Sun-pointing. This is suitable for applications in power generation but not for astronomy. Work is currently underway to determine how a non-azimuthally symmetric reflectivity profile across the membrane could be used to generate a parabola with an axis which is directed away from the Sun-line. It can also be envisaged that near Earth asteroid resources could be used to provide the bulk materials required to fabricate large numbers of ultra-large reflectors for interferometry. Indeed, if the manufacturing infrastructure is in place and bulk material is readily available then the marginal cost of each new reflector may be modest.

5. Accelerated manufacturing

If large parabolic reflectors could be fabricated using near Earth asteroid resources it also opens up the possibility of the reflectors being used to accelerate the processing of asteroid material itself. For example, a 500 m radius aluminium reflector with a thickness of $0.5 \text{ } \mu\text{m}$ has a mass of order 1 tonne and collects 1 GW of total power at the Earth's distance from the Sun. It appears then that industrial-scale power can in principle be generated via a relatively modest mass which could be delivered to Earth escape on a conventional launch vehicle.

After deployment the reflector could then use light pressure for propulsion (solar sailing) to reach a suitable M-type metal rich near Earth asteroid. With 1 GW of total power available the reflector could then liberate metals which could be manufactured into

additional reflectors, thereby accelerating the processing of the asteroid. In principle this accelerated processing is exponential, however due to the transport delay in turning metal into reflectors the total reflector area, and hence total processed mass, increases as a polynomial rather than exponential function of time. It could even be anticipated that the reflectors could spiral back to Earth orbit or the Lagrange points using light pressure. Here they would be collected and re-processed into other products for new applications. In this way the production and transport of bulk metals back to Earth orbit could be achieved using a modest initial investment in mass delivered to Earth escape. Other scenarios for bootstrapping large-scale industrialisation of space using robotics and automation have been considered with an initial seed mass as low as 12 tonnes [13].

6. Conclusions

It is clear that near Earth asteroids represent a vast potential resource of in-situ material, although the material resource has a spectrum of accessibility starting from the most easy to reach targets. Bulk materials can therefore be sourced from near Earth asteroids, reducing the launch cost of future science missions. Such bulk material could in principle be used, with novel fabrication methods such as additive layer manufacturing, to assemble large reflectors for optical or radio astronomy. Indeed, very large numbers of reflectors could be assembled for interferometry. While near Earth asteroid resources could provide bulk material, specialised components such as instruments and detectors would be launched from Earth. Clearly, such ventures are speculative, but the development of the infrastructure to capture and process near Earth asteroid resources could offer significant and exciting new opportunities for space science in future.

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What can space resources do for astronomy and planetary science?



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ABSTRACT

The rapid cost growth of flagship space missions has created a crisis for astronomy and planetary science. We have hit the funding wall. For the past 3 decades scientists have not had to think much about how space technology would change within their planning horizon. However, this time around enormous improvements in space infrastructure capabilities and, especially, costs are likely on the 20-year gestation periods for large space telescopes. Commercial space will lower launch and spacecraft costs substantially, enable cost-effective on-orbit servicing, cheap lunar landers and “interplanetary cubesats” by the early 2020s. A doubling of flagship launch rates is not implausible. On a longer timescale it will enable large structures to be assembled and constructed in space. These developments will change how we plan and design missions.

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1. More light

Like the great poet and polymath Goethe, astronomers will be calling for “more light” on their deathbeds (Fig. 1).¹ We are always seeking larger telescopes to collect the faint light arriving from the most distant stars, galaxies and quasars in the earliest times of the Universe; or else we are slicing up the light from bright stars exceedingly fine to look for signatures of small planets, other earths. There is no limit to what we crave. But we are in trouble. Our telescopes have grown in expense far faster than the economies they depend on. “*If something cannot go on forever, it will stop*” as Herbert Stein’s Law states in economics [1]. What can we do to ensure that ever greater observatories lie ahead?

The new large space telescopes now being discussed will not launch for 15–25 years. On that timescale much is going to change that could help our field. In this paper I look at the rapid developments occurring in commercial space activities and examine how they could provide a way out of our dilemma.

These developments are numerous. In Fig. 2 the timelines for major astronomy decisions to be made is compared with that for major developments anticipated for commercial space, including space resources. Clearly many relevant commercial space activities are set to happen before the next generation of major astronomy

observatories are launched, or even begin their final design/build stages (phase C/D in NASA terminology). Planning to take advantage of these developments would seem advisable.

2. The funding wall

Astronomers are already planning telescopes for the late 2020s. For example, the X-ray telescope ATHENA² has been selected as the second European Space Agency (ESA) Large mission (L2). It has an intended launch date of 2028. In the US the jostling for position to be given the #1 recommendation for large space missions in the 2020 “decadal study” has already begun. The astronomy management organization AURA has issued a report entitled “From Cosmic Birth to Living Earths”.³ This report advocates for a telescope double the size of the *James Webb Space Telescope* (JWST) to take this #1 spot. This “High Definition Space Telescope” (HDST) would have advanced coronagraphic (starlight-suppressing) optics that would allow it to directly detect the light from a twin of the Earth around nearby stars. Their nominal launch date is 2035.

Why plan so far ahead? Are astronomers just keen on delayed gratification? There is a deeper reason for these long timescales.

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¹ In Goethe’s case this may well be mythical; for astronomers, not so much.

² <http://sci.esa.int/cosmic-vision/54517-athena/>.

³ <http://www.hdstvision.org>. See also my critique: arXiv:1509.07798, and the response: arXiv:1511.01144.

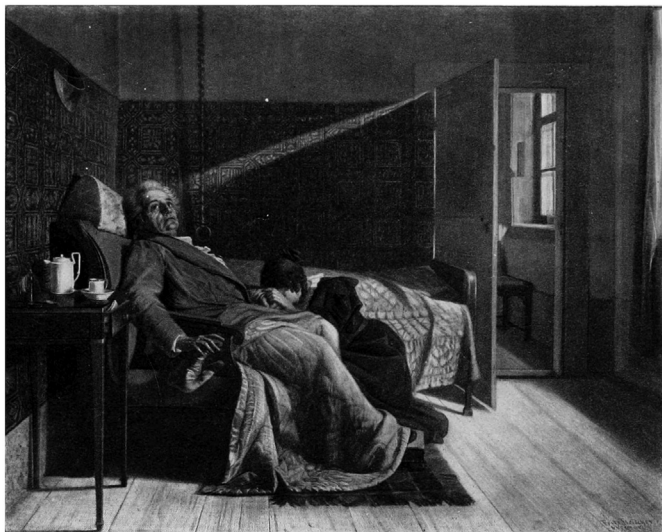


Fig. 1. Johann Wolfgang von Goethe calls for more light on his deathbed (F. Fliescher; source: commons.wikimedia.org).

2.1. Growing ambitions, growing costs

The reason we are making plans so far in advance is that our telescopes, in every band of the electromagnetic spectrum, have grown over the past few decades from small exploratory devices to Great Observatories. These flagship missions have enormous costs and take many years from conception to launch.

The prototypes for *Hubble* were space telescopes looking in ultraviolet light (which does not get through our atmosphere): the *Copernicus* Orbiting Astronomical Observatory, followed by the *International Ultraviolet Explorer* (IUE). These carried quite modest 80 cm and 45 cm diameter mirrors, respectively. *Hubble* has a 3–5 times larger mirror. JWST, billed as *Hubble's* successor, has a 6.5 m telescope, almost 3 times larger still. If built, HDST would be another doubling. This tendency to grow in jumps of 3 or so in diameter, or about 10 in mirror area, is exponential growth. It is baked into our research programs, as discoveries just possible with the previous generation always need more light to discern what they are and how they work. Without an order of magnitude leap in at least one capability there is virtually no chance that your favorite flagship will fly. The problem is that, historically, larger telescopes cost more.

Cost growth can be tracked for any class of space missions. For many years my field was X-ray astronomy. The breakthrough satellite missions⁴ came from NASA and were: *UHURU* (SAS-A, launched in 1970), the *Einstein Observatory* (HEAO-B, launched in 1978) and *Chandra* (AXAF, launched in 1999). Over the course of these 3 decades X-ray astronomy gained a factor of over 1 million in sensitivity. That is a truly huge advance, and is something that took optical astronomy about 200 years. The resulting impact on astrophysics was profound [2].

But the price was high. Fig. 3 shows how the (inflation-corrected) cost of these missions increased by a factor of about 20 over 30 years. This is an exponential growth rate of 10% per year. The same plot for other wavelength bands would be much the same. Ian

Crawford has shown that Mars landers have grown even faster, at about 15% per year [3]. Historical growth rates for the US GDP have been fairly steady at about 2% a year for the past century and more (1871–2001).⁵ Clearly, growth rates for astronomy that are four times faster than that of the economy are unsustainable.

Exponentially rising curves become all but vertical, so this mismatch of rates is often called “the funding wall” [4]. At some point the costs are more than a government can abide. Particle physics hit its funding wall in the US when the Superconducting Super-Collider, already far along in construction in Texas, went over budget one too many times and was cancelled.⁶ Is astronomy next?

We may well be up against the funding wall right now. JWST is costing NASA almost \$9 B up through launch in 2018, with another \$1 B or so coming from ESA and Canada. Cost growth led to repeated cancellation threats but a de-scope in 2001 and a re-plan in 2011⁷ averted this [5]. The HDST concept, AURA officials suggest,⁸ would cost about the same, though many outsiders are quietly skeptical that it would be so cheap. NASA currently has a budget of about \$5 B per decade for large new space telescopes.⁹ Each JWST-class mission thus takes 100% of nearly 20 years of this funding line. So building HDST by 2035, about 10 years after the launch of the Wide-Field Infrared Survey Telescope (WFIRST) in the early 2020s¹⁰, would require roughly doubling the available budget. A few billion more for such a major mission does not sound like an impossible target. But there is a catch.

2.2. The need for pan-spectral coverage

The problem is that modern astrophysics depends on simultaneous access to the entire electromagnetic spectrum. Stars, galaxies, quasars, and even planets, blithely ignore the limitations of our technologies, emitting light across all wavelengths, from the radio and infrared to the optical, ultraviolet and X-rays. Once astronomers see a cosmic object across the spectrum problems that had seemed deeply mysterious are answered, like jigsaw pieces fitting together, as in the case of the “exploding galaxy” Messier 82 (Fig. 4).

No one observatory can give the whole picture; together the story is clear: a giant burst of star formation in the center of the Messier 82 galaxy (*Hubble*, in green) forces a huge plume of gas heated to millions of degree (*Chandra*, in blue) out of the spiral disk, following the path of least resistance, with cool gas and dust following it around the edges. Here we are witnessing the process of young massive stars exploding as supernovae and sending their newly synthesized elements into space. It is from such materials that planets, and us, are formed. There are many such examples. They are the norm in 21st century astrophysics.

The synergy between these spectrum-spanning telescopes is surely a major reason that we are in a Golden Age of Astronomy.

We have been very fortunate, in fact, that this synergy has already lasted for 35 years, beginning around 1980 when we had

⁵ The fastest decade of growth in US GDP since 1871 was in the 1941–1950 decade when the rate reached 3.87%. <http://socialdemocracy21stcentury.blogspot.com/2012/09/us-real-per-capita-gdp-from-18702001.html>.

⁶ Appell, D., (2013), <http://www.scientificamerican.com/article/the-supercollider-that-never-was/>.

⁷ <http://www.space.com/12759-james-webb-space-telescope-nasa-cost-increase.html>.

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⁹ http://files.aas.org/head2015_workshop/HEAD_2015_Paul_Hertz.pdf, integration of slide.14.

¹⁰ <http://www.nasa.gov/content/goddard/qa-session-about-nasas-wfirst-mission>.

⁴ With apologies to the many other fine missions that did sterling work, including Ariel V, which I used for my PhD thesis. Nonetheless, the factor 100 steps in sensitivity were those listed.

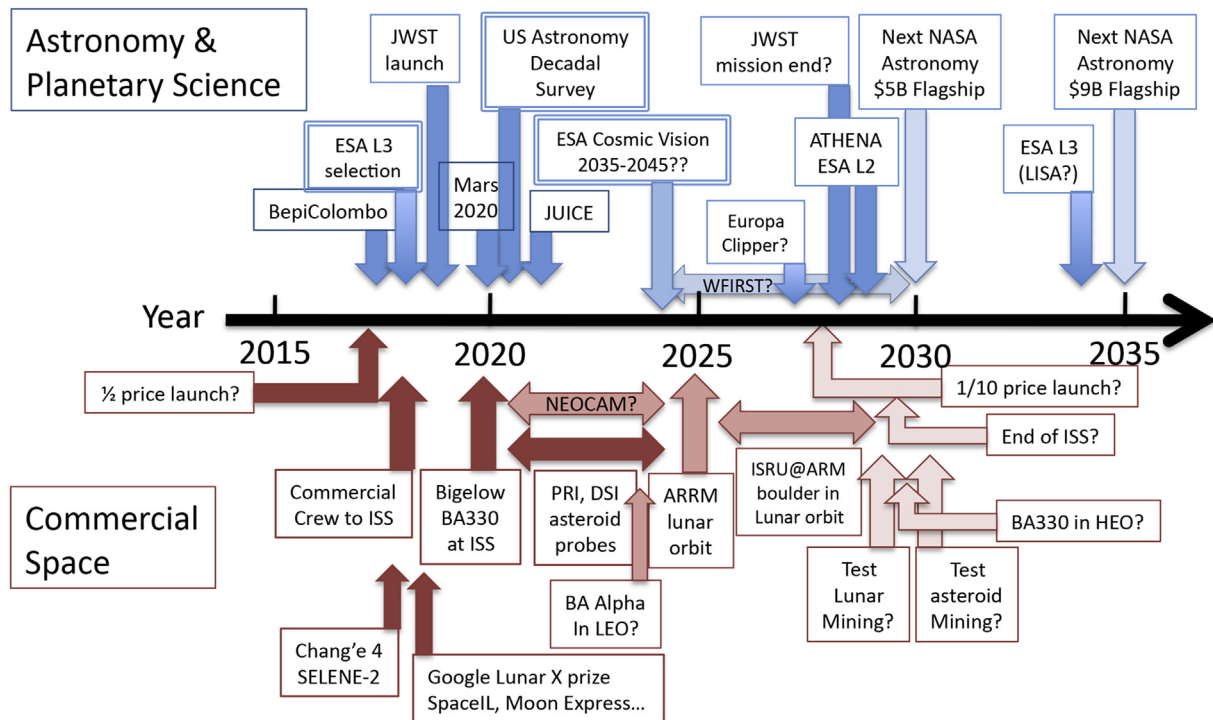


Fig. 2. Comparison of timelines for astronomy and commercial space and space resources, including NASA activities that promote them. The “Next NASA Astronomy Flagship” markers assume a constant budget for large new astrophysics missions at NASA and no substantial external contributions. NEOCAM and ARRIM are possible NASA missions, but they will enable commercial space ventures.

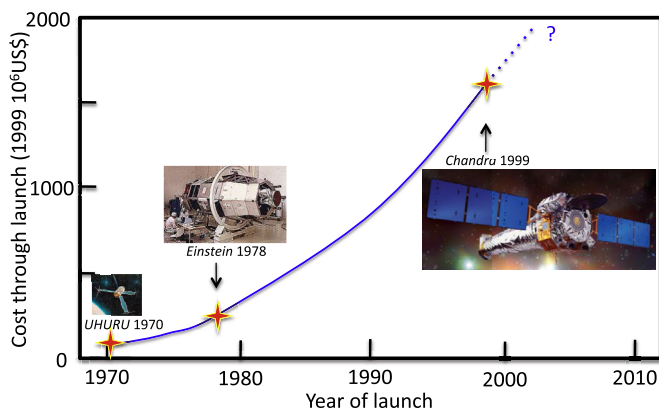


Fig. 3. Cost growth of leading X-ray astronomy missions, 1970–1999. Cost is given in constant 1999 US dollars: \$20 M for *Uhuru* (1970\$); \$100 M for *Einstein* (1978\$); \$1.6 B for *Chandra* (1999\$). H. Tananbaum, private communication. (Inflation corrections from US Bureau of Labor Statistics; URL: http://www.bls.gov/data/inflation_calculator.htm).

IRAS,¹¹ *IUE*¹² and *Einstein*¹³ (and then *ROSAT*¹⁴) in quick succession spanning the infrared, ultraviolet, and X-rays respectively, right up to the present generation of Great Observatories: *Spitzer*, *Hubble* and *Chandra*. For virtually this entire time a discovery in one

wavelength band could be followed up in the others just a year later. But the youngest of the three Great Observatories is 13 years old, and they cannot all be expected to last through the JWST era.

Even if they do survive they will not be matched to JWST's sensitivity. JWST will greatly surpass *Spitzer*'s infrared capability after it launches in 2018. However, there is no chance that we will have matching ultraviolet or X-ray capabilities until 2030 or later. By then the JWST 5.5–10-year lifetime¹⁵ will be over.

So following up a JWST discovery at another wavelength must wait, not a year, but a decade or more. The faint infrared glow from the earliest times in cosmic history (at $z > 10$) will have to wait patiently for an X-ray measurement to tell us if it is powered by the first stars forming, or by an adolescent black hole having a growth spurt. When we do get that X-ray measurement we will find that no discovery with that new X-ray flagship can be followed up until JWST too is replaced.

That kind of long delay will slow progress in the field to a crawl compared to today. Not the least effect will be that the dimmed excitement will put off talented young scientists from entering astrophysics.

Planetary science is similarly hindered by high mission costs. The 2011 Planetary Science Decadal report “Vision and Voyages” recommended three large-class missions, one each to Mars, Europa and Uranus.¹⁶ But only one can be done per decade,¹⁷ making this a

¹¹ IRAS 1983, January–November. (URL: <http://www.jpl.nasa.gov/missions/infrared-astronomical-satellite-iras/>). As IRAS was an all-sky survey later UV and X-ray discoveries could all still be followed up in the IRAS archive, despite its short lifetime.

¹² IUE 1978–1996 (URL: <http://science.nasa.gov/missions/iue/>).

¹³ Einstein 1978–1981 (URL: <https://www.cfa.harvard.edu/hea/hm/heaob.html>).

¹⁴ ROSAT 1990–1999 (URL: <http://www.mpe.mpg.de/xray/wave/rosat/mission/rosat/index.php>).

¹⁵ Limited by station-keeping hydrazine fuel supply. A few year extension may be possible. http://jwst.nasa.gov/faq_scientists.html#lifetime.

¹⁶ Vision and Voyages for Planetary Science in the Decade 2013–2022 (2011) <http://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022>.

¹⁷ Although the Europa mission was revived in a cleverly designed cheaper mission, *Europa Clipper*, it now seems unlikely to launch before the “late 2020s” (<http://www.space.com/31887-nasa-europa-mission-launch-late-2020s.html>); the once per decade cadence remains in place.



Fig. 4. The 'exploding galaxy' Messier 82, seen in optical, infrared and X-ray light with *Hubble*, *Spitzer* and *Chandra*, NASA's three Great Observatories. No one observatory gives the whole picture; together the story is clear (URL: http://chandra.harvard.edu/photo/2006/m82/m82_comp.jpg).

30-year program for even the top handful of priorities. The Mars mission was chosen,¹⁸ and it is only the first half of a Mars sample return program. Yet the more we learn of Solar System worlds the more we realize what we don't know. The 2015 New Horizons encounter with Pluto demonstrated this once again.¹⁹ This is not exploring the Solar System at scale. We need to do far more.

2.3. The crisis

Cost growth has created a crisis for both astronomy and planetary science. As noted in Section 2.1, a single new flagship following JWST and WFIRST might be as expensive as its ~\$9 B budget and yet launch relatively soon by obtaining a doubling of NASA's large astronomy missions budget. It is presently inconceivable though that we could obtain enough funding to launch four such flagships in a single 20 year span, maintaining spectral coverage. Some observing "window" will have to be let go. And that is ignoring the new field of gravitational wave astronomy [6]. Quadrupling or quintupling NASA's budget for large astrophysics missions would be a huge stretch. On this path we get our "Greater Observatories" sequentially.

And what would the longer-term prospect be even if we did quadruple the budget? What will we do when the science pushes us to even larger telescopes, or more ambitious ones? For example, an optical interferometer that can resolve the inner workings of quasars, and image continents and oceans on twins of the Earth orbiting other stars is an idea that has already been studied. It was called the "Terrestrial Planet Imager - Interferometer" (Fig. 5), but it has been set aside since 2008²⁰. We know how to build it conceptually, but it exceeds today's construction capabilities in space, and we can't afford it at current prices.

If we do not think creatively about this crisis we will all be competing for the one place at the shrinking water hole. This is an unattractive future for a great endeavor. It is one that effectively closes many of the observing windows we have opened in the past 50 years of the space age. How can we envisage a greater, open-

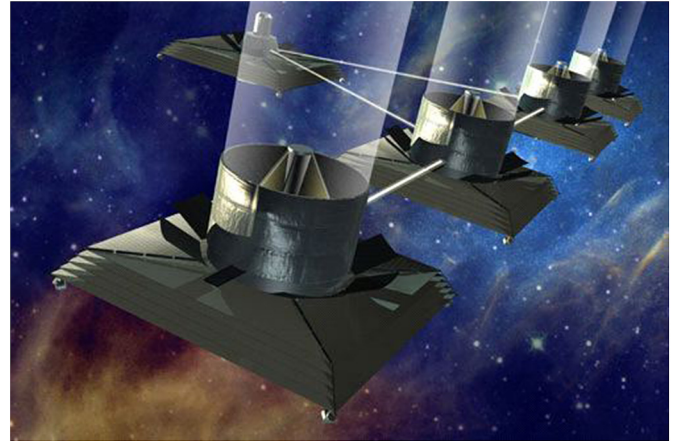


Fig. 5. Terrestrial planet imager - interferometer. (Source: NASA).

ended, future for astrophysics and planetary science?

The answer, I argue, lies in the commercial harnessing of space resources. Alan Stern, PI of the New Horizons mission to Pluto argues similarly [7]. Astronomers are planning on 20-year timescales, but are not yet fully aware of the major changes coming to commercial space activities in the next two decades. Most of us do know about SpaceX and its re-useable rockets, but perhaps not so much beyond that.

In the next section 1 look at the commercial space developments in the near-future to around 2020 and examine the effects they will have on astrophysics and planetary science planning. On this timescale the developments are quite predictable. In the following section 1 look out to the developments happening until around 2030, when the next flagship missions will launch. These are more speculative, but also more profound.

3. The near future to 2020

To date the only space resource used commercially has been non-material. Location is foremost. The few kilometer thick band of geostationary Earth orbit (GEO) has long been valuable real estate.²¹ Low Earth orbit (LEO) is newly prized as a location for constellations of for-profit Earth-observing satellites²² but is not yet in short supply. Micro-gravity is another non-material space resource for which new commercial uses are imminent.

So what can commercial space do for astronomy and planetary science? Potentially, it can do a lot. All commercial activities feel intense pressure to bring down costs in order to maximize profits, and commercial space is no different. Astronomy and planetary science can exploit these savings. How large could these savings be?

A rule of thumb is that launch and the science payload each consume about a quarter of a mission budget (up to launch), while the spacecraft consumes about half. Table 1 quantifies the potential gains on each element of a mission for factors 2–3 cuts in launch and spacecraft cost (As discussed in Section 3.3, science payload savings are capped at 50%). Not too surprisingly, for cost reductions of factors 2–3, similarly more missions could be flown.

There are five near-term areas where commercial space would effect changes: (1) launch cost reduction; (2) cheaper spacecraft; (3) cheaper payloads; (4) cheap, quick on-orbit testing; and (5)

¹⁸ in modified form as *Mars 2020* (<http://mars.nasa.gov/mars2020/mission/overview/>).

¹⁹ New Horizons web site: <http://pluto.jhuapl.edu>.

²⁰ https://exep.jpl.nasa.gov/TPF-I/tpf-I_what_is.cfm.

²¹ <http://history.nasa.gov/satcomhistory.html>.

²² <http://www.thespacereview.com/article/2716/1>.

Table 1
Potential effects of launch, spacecraft and science payload cost reductions.^a

	Earth orbit		
	Now	÷2	÷3
Launch	25	13	9
Spacecraft	50	25	17
Science Payload ^b	25	13	13
Total	100	51	39
Number of missions	1	2	3

^a All numbers rounded to avoid fractions.

^b Limited to factor 2 savings, as optics and sensors must remain state of the art (section 3.3).

cost-effective servicing. I consider each of them in turn in the following sections.

3.1. Reduced launch cost

The dramatic soft-landing of a Falcon-9 first stage on the barge *Of Course I Still Love You* in the Atlantic Ocean on the day this talk was given (8 April 2016)²³ made clear that re-useable rockets are rapidly coming of age. Stimulated by SpaceX, both of the traditional launch providers, Airbus and United Launch Alliance (ULA), announced their own variations on the concept in 2015.²⁴ In addition Blue Origin have demonstrated their New Shepherd re-useable first stage for sub-orbital flight and have made clear that an orbital version is planned.²⁵

The launch industry is on track to reduce launch costs substantially with these re-useable rockets. A factor 30%–50% cut in launch cost is possible for the first Falcon-9R commercial re-useable launch, probably in 2017.²⁶ As fuel accounts for only about ½ % of launch costs, factors of 10 or more price reductions are conceivable. For now the timescale to achieve such large factors is unclear. If SpaceX development goes as fast as they say, the late-2020s is a reasonable guess at when factors this large might happen.

If launch were to be 10 times less expensive this would provide a useful saving for a given mission, as launch typically amounts to ~25% of mission costs through launch. It would also improve the cadence of missions, building 4 in the time it would now take to fund 3. But launch savings alone are not enough to allow two major observatories to be built simultaneously. Even if launch were free it would not alone be enough to double the number of missions.

It is not cheaper launches by themselves that will change the economics of space missions, but their effect in enabling low cost spacecraft, as I discuss below.

3.2. Cheaper spacecraft

For most major astronomical observatories in space, the spacecraft is about half the cost. Cutting spacecraft cost by a factor 2, along with launch costs by a factor 3, would roughly halve the cost of a flagship mission. This would radically alter flagship

mission decisions, by doubling the number that could be launched each decade. This raises the question “Why are spacecraft so expensive?”

We usually use the term “aerospace engineering”. This gives the impression that designing aircraft and spacecraft are a single discipline. But in fact space engineering is driven by different considerations than aircraft engineering, and so is a different discipline. Above all, for space, mass matters. Mass is a consideration for aircraft design, of course. But minimizing mass in spacecraft is paramount, thanks to the ineluctable rocket equation that demands exponentially more propellant for linear increases in payload mass.

This focus on mass has consequences. On a spacecraft every kilogram, even every 100 g, has to be carefully argued for. This pushes spacecraft design toward designs using exotic components and relatively small performance margins, and that leads to rigorous design and test regimes. Each spacecraft, with the exception of communication satellites (comsats), is typically a bespoke tailored design. This approach makes spacecraft extremely expensive. For example, I sat in one meeting in which several well-paid engineers flew in to spend an afternoon learning the basics about a 100 g sensor that cost about \$1000, plus a meter or two of cabling. That one meeting cost more than the sensor, and it was the first of many on just that one small detail of the whole payload. Until we can relax the mass design constraint we will have highly costly spacecraft.

Mass is the driver for spacecraft design because of the daunting cost of getting to orbit, presently about \$10 k/kg to LEO. Reduced launch costs will have a knock-on effect, as the entire space engineering discipline will gain much greater flexibility about its design drivers. Using (relatively) massive spacecraft with large performance margins is now unaffordable. Once launch costs are cut by factors of a few then a “fat-sat” approach will be a natural path to lower cost spacecraft [8]. Sturdy spacecraft structures, multiply redundant electronics, electrically shielded cabling, larger solar arrays allowing the use of higher power consumption electronics are examples of the many ways in which spacecraft design constraints would be eased, and design/test cycles simplified. A Boeing study, cited in Refs. [8], indicates that a 50% growth in spacecraft mass could lead to a factor 3 reduction in spacecraft cost. If over-capable spacecraft are acceptable then they can be “off-the-rack”, like cubesats, rather than bespoke, and can reap the cost advantages of batch production.

This idea has a long history [8], but until now has lacked the necessary factor of about 3 reduction in launch costs to make the transition happen. By the mid-2020s this barrier should be gone (Section 3.1).

3.3. Cheaper science payloads?

The remaining big ticket item for a mission is the scientific payload. Telescope mirrors and other optics, sensors and pre-amp electronics typically all push the envelope of technology. They have to, in order to produce a major, world-beating, advance. This part of payloads is not likely to get cheaper.

Science payloads, though, include many other components too. These include: structures, power supplies, thermal control, downstream electronics and data processing. These components could benefit from the same design criteria relaxation as the spacecraft itself. Higher mass and power could be tolerated for them. What factor cost reduction this relaxation might enable has not yet, to my knowledge, been studied.

3.4. Passenger flights to orbit

The commercial launch of passengers into space is progressing fast. In the near future, by 2018, both SpaceX and Boeing will have

²³ <http://www.cbsnews.com/news/falcon-9-boosts-cargo-ship-to-orbit-sticks-ocean-landing/>.

²⁴ Airbus “Adeline” concept, June 2015: <http://www.space.com/29620-airbus-adeline-reusable-rocket-space-tug.html>; ULA Vulcan concept, 13 April 2015: <http://spaceflightnow.com/2015/04/13/ula-unveils-its-future-with-the-vulcan-rocket-family/>.

²⁵ <https://www.blueorigin.com/technology>.

²⁶ spacenews.com/spacex-says-reusable-stage-could-cut-prices-by-30-plans-first-falcon-heavy-in-november/; <http://selenianboondocks.com/2016/04/spacex-amateur-business-case-study/>; <http://spacenews.com/spacexs-reusable-falcon-9-what-are-the-real-cost-savings-for-customers/>.

operational spacecraft, *Dragon-2*²⁷ and *CST-100 Starliner*²⁸ respectively, transporting up to seven crew at a time to the International Space Station (ISS) as part of NASA's Commercial Crew Program.²⁹

Sub-orbital passenger spacecraft are also being developed as precursors to orbital capabilities. Although Virgin Galactic has been the highly visible face of sub-orbital space tourism for a decade, they do not seem to have a direct route to orbital flights. Instead other companies have clear development paths to orbit. Blue Origin, funded by Amazon founder Jeff Bezos, had a spectacular public debut in November 2015 when they separately soft-landed both their (empty) crew capsule and their single stage rocket back at the launch site. They are clear that they view sub-orbital as a natural path to orbital flights. Their commercial orientation is clear in the video they released³⁰. It touted "the largest windows in space", inviting comparison with Virgin Galactic. Advertising the final frontier may seem gauche, but it will pay the bills. Less splashy is XCOR.³¹ Their small Lynx spacecraft will begin, like Virgin Galactic, as a sub-orbital vehicle, but is designed to scale up to an orbital capability.³² Sierra Nevada may be a fourth orbital contender. For now their Dream Chaser is only slated for cargo delivery to orbit,³³ but this is actually a downscaling of their original personnel carrier.

If the market for orbital joy rides and for trips to commercial space stations (section 3.7) proves to be robust, there will be many companies competing for passengers by the early 2020s. XCOR is aiming for a ticket price of \$1 M to orbit. That is a price point that opens up many more customers, and can plausibly be matched by the other providers, if launch prices come down by an order of magnitude as SpaceX have often claimed.³⁴

3.5. Instrument testing on-orbit

The advent of commercial passenger transport will likely include opportunities for instruments as piggyback payloads. The *Dragon-2* "trunk" space is one location.³⁵ The *Lynx* is designed to carry external and internal payloads as alternatives to a passenger.³⁶

Already cubesats are starting to enable hardware tests to high technical readiness levels (TRL-7³⁷) at modest cost. Instruments that are too large for 3U or 6U cubesat formats, or that need more power than they can supply, could be tested in the space environment on passenger flights, although not in the integrated mission operations conditions needed for the top readiness level, TRL-9. A capability like this could accelerate the development, improve the reliability, and reduce the cost, of science payloads for large missions at modest cost. This could allow more advanced instruments to be flown at an earlier date.

3.6. Cost effective servicing in LEO

If space tourism extends to spacewalks (Extra Vehicular Activity

or EVAs in NASA-speak) then cost-effective on-orbit servicing in LEO will become feasible. The scientific value of on-orbit servicing of spacecraft is well-established. The five servicing missions for *Hubble* were dramatic technical successes.³⁸ The first, SM1, was a true *tour de force* by both the ground teams and the astronauts. SM1 corrected the aberration in the primary mirror, rescuing the mission. Subsequent missions replaced all the original instruments with new versions that were orders of magnitude better in some parameters, and extended the life of the mission by replacing key components that had failed (gyros and batteries) and by boosting *Hubble* to a higher orbit.

However, the cost of the *Hubble* servicing missions³⁹ was sufficiently high that the two successor Great Observatories were placed in orbits that could not be serviced. In the case of *Chandra* a highly elliptical orbit was deliberately chosen to prevent servicing, in order to keep down the post-launch run-out costs of the program⁴⁰ and avoid cancellation. This orbit turns out to have science advantages, but that was not the initial impetus for choosing it. *Spitzer* was put into a novel Solar drift-away orbit. This was chosen to reduce the heat load on the on-board cryogen so as to allow less to be carried aboard while keeping a 5-year cold mission lifetime. This change greatly reduced the mission mass and cost through launch, enabling the mission to be approved [9]. It also served to prevent any possibility of servicing, and so kept run-out costs down, as for *Chandra*.

With low cost human access to LEO, servicing can return to being a normal part of missions in accessible orbits. Replacing failed systems can allow higher risk profiles and so lower costs. A lost mission, such as *Hitomi*,⁴¹ might be revived at a fraction of the cost of a new mission, and a repair would likely be much faster to implement. On-orbit servicing could also encourage agencies to risk choosing more cutting edge instruments to be installed in telescope focal planes. An instrument failure then becomes a nuisance, not a mission-ending event. Astronauts valued the *Hubble* servicing missions highly. "As an astronomer and an astronaut, putting my two hands on *Hubble* in space was one of the greatest thrills of my life", says Jeffrey Hoffman⁴² who took part in SM-1. If servicing missions return, they would be motivationally valuable to the astronaut corps.

3.7. Commercial space stations in LEO

Timed to follow the introduction of commercial passenger flights to orbit, Bigelow Aerospace, now in partnership with ULA,⁴³ intends to launch its first BA330, 330 cu. meter, privately built and funded space station in 2020 to attach to the ISS. The primary resource provided there will be micro-gravity. Their idea is to rent out volume not only to the major space agencies, but also to large corporations, foundations and research organizations, as well as to countries wanting a cheaper route to a space program. If the ISS reaches its end-of-mission in 2024, as could happen, the BA330 could then be detached and operated independently.

An advantage of a free-flying Bigelow space station will be a major shrinking of the 2½ year training program for ISS-bound astronauts [10]. Such a long training for skilled bench scientists would be prohibitive for commercial companies. All the BA330

²⁷ <http://www.spacex.com/news/2014/05/30/dragon-v2-spacexs-next-generation-manned-spacecraft>.

²⁸ <http://www.boeing.com/space/crew-space-transportation-100-vehicle/>.

²⁹ <https://www.nasa.gov/exploration/commercial/crew/index.html>.

³⁰ <https://www.youtube.com/watch?v=9pillaOxGCo>.

³¹ <http://www.xcor.com>.

³² <http://spacenews.com/suborbital-vehicle-developers-looking-ahead-to-orbital-systems/>.

³³ beginning in 2019. <http://spectrum.ieee.org/tech-talk/aerospace/space-flight/nasa-contracts-dream-chaser-shuttle-for-space-station-resupply>.

³⁴ <http://arstechnica.com/science/2015/12/by-making-a-historic-landing-spacex-launches-new-age-of-spaceflight/>.

³⁵ <http://www.spacex.com/news/2013/03/26/dragon-trunk>.

³⁶ external: <http://science.xcor.com/payloads/external-payloads/>.

³⁷ https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html.

³⁸ http://www.nasa.gov/mission_pages/hubble/servicing/index.html.

³⁹ About \$1.2 B/mission (2010 dollars) in operating costs, discounting development costs: <http://www.space.com/11358-nasa-space-shuttle-program-cost-30-years.html>.

⁴⁰ Leary, W.E., 1998, <http://www.nytimes.com/1998/03/31/science/telescope-will-offer-x-ray-view-of-cosmos.html?pagewanted=2>.

⁴¹ *Hitomi*: http://global.jaxa.jp/projects/sat/astro_h/.

⁴² private communication, 20 April 2016.

⁴³ <http://spacenews.com/ula-and-bigelow-announce-partnership-for-launching-commercial-space-stations/>.

equipment will come from a single supplier and not, as on the ISS, from US, Russian, European and Japanese suppliers. This will simplify the training of the scientists who take passenger flights to orbit. Not being required to learn Russian or to spend long periods in Russia is another advantage.

We know how much customers would pay. Bigelow Aerospace advertises rates of \$25 M/110 cubic meters for 60 days.⁴⁴ That translates into a substantial \$450 M/year in revenue for one BA330 module. Their follow-on Space Station Alpha concept⁴⁵ has two BA330 modules and so would generate almost \$1 B/year in revenue, assuming customers materialize. NASA's Bigelow Expandable Activity Module on ISS⁴⁶ (BEAM, 2016–2018) is a first test of their technology with astronauts involved.

The main customers for a private space station may well be large biotech companies. Astronomers, including myself, have tended to think that no interesting laboratory research has been done at the ISS. We are not well-informed. In fact, gene expression can be radically altered in bacteria and plants grown in space [11] and the changes can be passed down to subsequent generations, even though they are back in Earth gravity. Biotech is a \$270 B/year research-intensive industry that is growing at 12% per year.⁴⁷ By 2020 biotech will be a half trillion dollar industry. If gene expression changes in low gravity are common, then it is highly plausible that biotech companies could put 0.2% of their revenue into space-based research, fully booking Alpha's facilities.

By 2020 then, when US astronomers sit down to contemplate their future in the next decadal study, it is plausible that a commercial laboratory in space will have begun, and by 2025 a free-flying commercial space station may well be operating.

The benefits of private research laboratories for astronomy and planetary science are less clear than the other developments. The BA330 does not have external trusses or platforms that could hold zenith, sky-pointing, pointing telescopes. (Nor could it accommodate nadir, Earth-pointed, instruments.) A specialized BA330 fitted out for cosmic ray detection is a possibility, but this is a relatively narrow application.

The main benefits would probably be the increased traffic to LEO that it would generate. If 2 months and 110 m³ is the standard rental, then there would be 6 teams on-board Alpha with changeovers 6 times/year. If a team is 2 scientists (e.g. to work in shifts), then 12 flights/year using CST-100/Dragon-2 on Atlas-V/Falcon-9 class launchers would be needed to ferry up the scientists. That implies monthly crewed flights. While this is a minor increment to the current ~50 flights/year of this vehicle class, it is a factor 4 increase over the present rate of crewed flights of ~4 flights/year.⁴⁸ Together with orbital tourism, these flights would make on-orbit testing (section 3.5) and servicing (section 3.6) more routine.

3.8. Private lunar landers

Several countries are already planning or executing lunar lander programs. China put *Chang'e 3* and its *Yutu* rover onto the Moon in 2013, demonstrating technological readiness. The follow-up *Chang'e*

4 mission is planned to land on the lunar far side.⁴⁹ Japan's JAXA space agency should fly the SELENE-2 lunar lander [12] in 2017.⁵⁰

On the non-state actor side, the Google Lunar X-prize⁵¹ has inspired academic groups, non-profits and private companies alike to design cheap lunar landers. The \$30 M Google Lunar X-Prize will close out at the end of 2017. As of writing two teams have launches booked in 2017: SpaceIL with Space X, and Moon Express with Rocket Lab USA. (Rocket Lab's *Electron* rocket had not flown as of writing.⁵²) Moon Express has 3 dedicated flights reserved at a reported \$5 M per flight.⁵³ Moon Express plans to attempt lunar sample return by the third flight ~2020. Moon Express in particular has a clear commercial focus for its MX-1 spacecraft/lander. Prices are claimed to be "less than \$50 M".⁵⁴

For astronomy these small landers offer little at first. They may enable prototype far-side very low frequency (<30 MHz) radio telescopes.

For planetary science the advantages of these small landers are clear. There have only been a few lunar sites visited with scientific equipment. These were all chosen decades ago, long before the Moon was mapped in detail. Today we have kilometer scale or better measurements of the Moon at many wavelengths, plus detailed gravity maps [13]. These maps show that the Moon is highly non-uniform and they highlight very many places that planetary scientists would like to land, study, and from which they could return samples. The Lunar Geophysical Network, for example, proposed as a NASA New Frontiers mission may be enabled by this new capability. Well-chosen locations for ground truth will also multiply the value of the global surveys from lunar orbit.

3.9. Asteroid prospecting

Asteroid mining companies have been in the news quite a bit. There are two main ones: Planetary Resources Inc.⁵⁵ and Deep Space Industries.⁵⁶ Both plan to mine water from near-Earth asteroids as their first "ore", and both expect to send out their first small experimental interplanetary spacecraft to asteroids within 5 years. Water ore bodies among the asteroids may be relatively hard to find [14] requiring large numbers of probes, each one of which must then be cheap in order to close the business case.

The interplanetary cubesat-class spacecraft being developed for asteroid prospecting⁵⁷ are intended to cost around \$5 M each, an extraordinarily low price. Their instrument-carrying capacity is small in mass and volume (~1 kg, ~1U, i.e. 10 × 10 × 10 cm). Nonetheless, they offer the opportunity to field large numbers of highly targeted planetary missions to the Inner Solar System, and to do so quickly.

By 2020 the companies may be ready to sell copies of these spacecraft for science missions. For planetary science, as there are 24 different sub-types of asteroids [15], a fleet of small missions, with very limited instrumentation on each, could be considered to explore them all. The cost of this fleet would likely be less than that

⁴⁴ <http://www.nasaspacesflight.com/2014/02/affordable-habitats-more-buck-rovers-less-money-bigelow/>.

⁴⁵ <http://www.space.com/19291-inflatable-alpha-station-bigelow-aerospace.html>.

⁴⁶ Launched on the day this talk was given, 8 April 2016. http://www.nasa.gov/mission_pages/station/research/experiments/1804.html.

⁴⁷ <http://www.grandviewresearch.com/industry-analysis/biotechnology-market>.

⁴⁸ for 2015: https://en.wikipedia.org/wiki/2015_in_spaceflight.

⁴⁹ Space Daily, 22 May 2015. 'China Plans First Ever Landing On The Lunar Far Side'. http://www.spacedaily.com/reports/China_Plans_First_Ever_Landing_on_the_Dark_Side_of_the_Moon_999.html.

⁵⁰ <http://www.cnn.com/2015/04/23/tech/japan-moon-lander-planned/> (accessed 15.07.15).

⁵¹ <http://lunar.xprize.org> (accessed 15.07.15).

⁵² A mid-2016 launch was planned as of writing (<http://spacenews.com/rocket-lab-plans-to-begin-launches-mid-year/>).

⁵³ http://www.nzherald.co.nz/nz/news/article.cfm?c_id=1&objectid=11300831.

⁵⁴ Richards, R., presentation to European Space Policy Institute, Vienna, Austria, 2016, April 16: <https://www.youtube.com/watch?v=ealvx3Gx1Mw>.

⁵⁵ <http://www.planetaryresources.com>.

⁵⁶ <http://deepspaceindustries.com>.

⁵⁷ "Arkyds" by Planetary Resources (<http://www.planetaryresources.com/arkyd/>); "Fireflys" by Deep Space Industries (<http://deepspaceindustries.com/prospecting/>).

Table 2
Commercial Space activities effects on Astronomy and Planetary Science to 2020.

Commercial space activity	Effect on cost	Value to astronomy, planetary science
Lower cost launch ($\geq 2X$)	Cheaper Spacecraft. (factor 2–3?, “off-the-rack”) Cheaper science payloads (factor 2?)	“2 for 1” missions, both astronomy and planetary science
Passenger flights to LEO	Cheap High TRL tests Cost-effective servicing in LEO	Cutting edge instruments Higher risk sub-systems in LEO
Private Space Stations	More passenger traffic	Indirect via more passenger flights
Private Lunar Landers	Cheaper access to lunar surface	Many expeditions to scientifically interesting sites
Asteroid Prospecting	Cheaper access to inner Solar System	Many specialized missions to all near-Earth asteroid types

of a single NASA New Frontiers mission (~\$700 M for New Horizons⁵⁸) and so would be something of a paradigm shift from the current approach of sending one heavily instrumented spacecraft to a single destination (e.g. OSIRIS-REx [16]).

3.10. The state of play in 2020

It is useful to bring together all the developments considered so far along with their implications for astronomy and planetary science. Table 2 summarizes the situation.

These are mostly highly probable developments. Together they will significantly change the landscape in which astronomers and planetary scientists plan their next steps. Cheaper launch and spacecraft, with on-orbit servicing will likely be the first significant gains for science to result from commercial space. In this way location and micro-gravity can be helpful space resources even before material space resources are exploited. Other changes will take longer, as we shall see next.

4. Longer term to 2030: material space resources begin to matter

To properly match the astronomers' planning horizon we need to look ahead by another decade, to 2030. Plans on that timescale are necessarily more speculative, yet there are enough indicators that we can make reasonable extrapolations. The big change is the move away from LEO as the use of material space resources begins. The benefits of the beginning of lunar and asteroid mining for astronomy and planetary science now begin to be large. These benefits lie in three areas: (1) on-orbit assembly; (2) on-orbit construction; (3) rapid Solar System transit times. First I describe the potential developments, then I cover each of the three areas in turn.

4.1. A private space station in high orbit

It is quite plausible that by 2030 a commercial space station could have been placed in a high orbit, perhaps at the Earth-Moon L1 Lagrange point (EM-L1). The commercial motivation for doing so is to attain true micro-gravity. A government laboratory would have the same imperative and both may be deployed.

Atmospheric drag and gravity gradient torques limit ISS and other LEO stations to milli-gravity [17]. Sensitive experiments will benefit from the quieter environment at a Lagrange point, far from atmospheric drag and at zero gravity gradient. To maintain micro-gravity astronauts could not live on such a station. They could visit to tend the experiments, fix hardware, resupply consumables, or retrieve products.

A deep space, e.g. EM-L1, space station could act as a catalyst for commercial space mining operations. The radiation environment outside the radiation belts and specifically at EM-L1 is much worse than in LEO. Genetic experiments must be sensitive to radiation

dosage. Hence to control the experimental conditions biotech companies will require heavy shielding. A naïve calculation making the mass of shielding equal to the mass of the Earth's atmosphere at sea level suggests of order 10 tons of shielding per square meter. Hence thousands of tons of shielding would be needed for any reasonable sized laboratory. Water makes good radiation shielding and this could become a usefully large market for resources from space.

Space-supplied shielding is natural to consider as, in such high orbits, it is energetically much cheaper to bring the raw materials for these activities from the Moon or from some near-Earth asteroids. It may even be economically cheaper: even if launch costs come down by a factor 10 the price is still \$1 M/ton from Earth to LEO.⁵⁹ To reach high orbits would multiply the cost of supplies from Earth by another factor 2–3. At these rates adding a thousand tons of shielding makes even a cheap space station into a billion dollar plus investment again all too quickly. That's a daunting figure for a commercial company. If space-derived materials could be supplied for, say, a quarter the price, then there would be an opening for both space miners and deep space research stations to flourish. That is a big if, of course.

The value of an EM-L1 station for both astronomy and planetary science is quite major. Both cargo and passenger transport from LEO to EM-L1 will be needed. This will enable deep space servicing of astronomical telescopes. The Earth-Sun L2 point (ES-L2) is 1.5 million kilometers from Earth, about 4 Lunar distances. ES-L2 is a favorite location for sensitive astronomical observatories. *Herschel*, *Planck*, and *JWST* all use this orbit. With a delta-v of 0.4 km s⁻¹ [18] it is energetically easy to reach ES-L2 from EM-L1. Planetary Science will gain the ability to fuel interplanetary probes at the top of the Earth's gravity well, enabling large payloads to be delivered.

Will suppliers of water, or other shielding material, from space resources be ready to meet the demand? Next I look at the feasible state of development of asteroid and lunar resources by 2030.

4.2. Asteroid resources

On the 2030 timescale several developments will combine to make true asteroid mining plausible.

- (1) By 2025 the two asteroid mining companies should be sending out fleets of their cheap “interplanetary cubesat” spacecraft to asteroids that look like good mining prospects (see section 3.7). By 2030 these proximity probes should have found several ore-bearing, i.e. profitable, asteroids. [The knowledge of which ones they are will, of course, be intellectual property (IP) belonging to the companies. Science will not benefit directly from that knowledge.] So the first robotic mining forays can begin around 2030.
- (2) High power solar electric propulsion (SEP) will also have been demonstrated by 2025. This will enable interplanetary orbits for larger spacecraft. NASA's Asteroid Redirect Mission (ARM) will use 40 kW SEP to move a 7–10 ton spacecraft, including the

⁵⁸ p.4 of https://www.nasa.gov/pdf/139889main_PressKit12_05.pdf.

⁵⁹ Metric units used throughout. 1 mt = 1000 kg = 2204 lb = 1.1 US ton.

xenon propellant [19] out to a near-Earth asteroid. This class of SEP is sufficient to return substantial material mined from an asteroid. The ARM spacecraft will take ~2 years to return a ~10 ton boulder⁶⁰ to a lunar orbit in ~2021. If more accessible asteroids can be found this mass can go up to 1000 tons [20].

- (3) Astronomical surveys for near-Earth asteroids (mainly supported by NASA) will have found vastly more objects by 2030. The Catalina Sky Survey⁶¹ in Arizona and Pan-STARRS⁶² in Hawai'i are progressing apace, at a rate of ~1500/year in 2015, to a current total of ~14,000. This rate will accelerate in 2016 once Pan-STARRS-2 and ATLAS⁶³ come on line. A naïve projection is that 30,000 near-Earth objects will be known by 2030 from these surveys. When the Large Synoptic Survey Telescope (LSST) comes on-line in the early 2020s it will find many more near-Earth asteroids [21]. Many of these near-Earth asteroids will be small and must have orbits bringing them especially close to the Earth just to be detected. This could provide a supply of lower delta-v asteroids in the 1000 ton class that could be excellent mining targets, especially for water. If NASA approves the JPL NEOCAM⁶⁴ mission then from about 2021 to 2023 a thermal infrared survey will catalog some 100,000 near-Earth objects, and get good sizes for them.

Asteroid miners need additional serious astronomy to do two essential things: (1) get precise orbits so that newly discovered asteroids, which are mostly small (100 m diameter or less) are not lost again, and (2) get a first order clue to the composition of the asteroids of interest. (I.e. are they stony, carbonaceous or metallic?). Among optically discovered asteroids 85% are found to be stony and so not too interesting for asteroid miners as they are low in water or precious metal content [14]. Hence just being able to rule out the stony asteroids will increase the pay-off from proximity prospecting probes seven-fold. Professional astronomers using a 4-m class telescope with optimized instrumentation could do both jobs. The venture could be undertaken as a government, philanthropic or commercial project [22].

- (4) The challenges of working with a large “uncooperative” mass in zero-g are not trivial, and matter greatly to would-be asteroid miners. These same challenges will be addressed by NASA's Asteroid Redirect Mission (ARM),⁶⁵ which is planned to return a multi-ton boulder from an asteroid to a lunar orbit by the mid-2020s. Once returned, commercial companies may be invited to test mining techniques on a small scale on this boulder. So by around 2030 there should be established beneficiation (ore-concentration) techniques that have been tested in space.

4.3. Lunar resources

Given that no-one has been to the Moon for over 40 years, lunar mining may seem unlikely. Here too developments are promising for the use of lunar resources.

Multiple spacecraft have mapped out the Moon's composition – its resources – over the past decade [13]. The resulting maps show a

varied, highly clumped, distribution of interesting materials.⁶⁶ Some parts of the Moon are far more useful than others. The permanently dark craters at the lunar poles are foremost in this list, as they seem to have preserved volatiles, including water deposited there by asteroids and comets eons ago. As a commercial mining site the Moon has advantages over asteroids. Having some gravity can be helpful in mining and refining operations. Also the Moon is always in essentially the same location, and so is permanently accessible with short journey times of a few days. The time cost of money makes flexible access and short transit times important to a business.

Shackleton Energy⁶⁷ has ambitious plans to mine water commercially from the South Pole permanently dark craters. There are other permanently dark craters, but Shackleton crater at the South Pole of the Moon is special in that there are a series of thin ridges and crater rims just a few kilometers away that are in near permanent sunlight. These poetically named “Peaks of Eternal Light” [23] could provide a cheap continuous power source for mining the water. The solar panels would have to be mounted several meters above ground for truly uninterrupted power. The Peaks of Eternal Light cover less than 1 sq. km, and so are a scarce resource that will be a source of potential conflict if lunar mining becomes a real industry [24].

So the first commercial extraction of lunar resources is looking plausible by 2035.

4.4. Lunar telescopes

Traditionally the main band in which a lunar observatory has an advantage is low frequency radio telescope on the far-side, where it would be shielded from terrestrial interference. A large version of this telescope with long baselines to obtain good angular resolution would be straightforward to construct if we have the capability to mine the lunar surface. We would need to take care than any GPS system or comsats in lunar orbit do not produce interference for this telescope.

Lunar near-side short wavelength (sub-mm) telescopes working in concert with the very long baseline interferometer (VLBI) Event Horizon Telescope (EHT)⁶⁸ would allow the EHT to image the event horizons of ~30 supermassive black holes, rather than the 2 that are accessible using Earth diameter baselines. Implementing VLBI requires knowing the separations of the telescopes to a fraction of a wavelength. The Moon provides a far more stable baseline than any spacecraft can currently offer.

A newly emerged possibility is that of large lunar mid-to far-infrared telescopes. The JWST primary mirror is cooled to ~50 K which allows it to be sensitive out to 24 μm wavelengths.⁶⁹ Designing a system to keep this 6.5 m diameter mirror at this low temperature is a challenge. In part because of this problem the HDST concept eschews wavelengths longer than about 3 μm . There are large areas inside the permanently dark craters near the lunar South Pole with stable temperatures of 25 K (about –250 C) [25]. These sites could be valuable for much larger mid-to far-infrared telescopes, including interferometers, that could work out to at least 50 μm wavelengths. On the 2035 timescale these possibilities may well become feasible. They would need to keep some distance from mining operations to avoid dust settling on their mirrors. Perhaps some permanently dark craters should be set aside for astronomy.

4.5. On-orbit assembly

Valid concerns over reliability have led the space agencies to be

⁶⁰ Chodas, P. (2015) http://www.lpi.usra.edu/sbag/meetings/jan2015/presentations/SBAG12_ARM_Candidates_Chodas.pdf.

⁶¹ <http://www.lpi.arizona.edu/css/>.

⁶² <http://pan-starrs.ifa.hawaii.edu/public/asteroid-threat/near-earth.html>.

⁶³ <http://fallingstar.com/home.php>.

⁶⁴ <http://neocam.ipac.caltech.edu>; <http://www.lpi.usra.edu/sbag/meetings/jan2016/presentations/Mainzer.pdf>.

⁶⁵ https://www.nasa.gov/mision_pages/asteroids/initiative/index.html.

⁶⁶ Crawford also gives a convincing critique of the case for ³He mining on the Moon.

⁶⁷ <http://www.shackletonenergy.com>.

⁶⁸ <http://www.eventhorizontelescope.org>.

⁶⁹ The smaller (0.85 m) infrared Spitzer Space Telescope was initially cooled to about 5 K and was sensitive out to 160 μm .

extremely wary of moving parts in their spacecraft. As telescopes sizes come to exceed the limits of launcher fairings however, unfolding spacecraft designs are being used. From the relatively simple extending optical benches employed in Japanese⁴² and US X-ray missions⁷⁰ (for which long focal lengths are inescapable), to the complex unfolding of the JWST mirror assembly and thermal shields,⁷¹ on-orbit deployment is becoming necessary for astrophysics missions. Launcher fairings are presently about 5 m in diameter. The limit of mirror diameter achievable by unfolding from a 5 m fairing⁴ appears to be ~12 m. The later (Block 2 B, late 2020s) SLS fairing is intended to reach 10 m.⁷²

In order to build the larger telescopes that astronomers need (Section 2) we will at some point have to go to the next step: on-orbit assembly. For example, any version of the Terrestrial Planet Imager - Interferometer involves linking several smaller telescopes with tethers or trusses (Fig. 4, Section 2.3). Telescopes like these will need on-orbit assembly, using pre-built components being delivered on separate (lower cost) launchers.

Missions to the Outer Planets would benefit in either transit time or delivered mass from on-orbit mating to a fully-fueled upper stage, or re-fueling of its own upper stage (Section 4.2). Longer magnetometer booms are desirable. Larger communications antennae and solar panel arrays could also use on-orbit assembly and may be mission enabling.

Similar assembly capabilities will need to be developed for lunar or asteroid mining operations. Extracting 1000 tons of water from a 10,000 ton, or larger, asteroid is challenging. A sufficiently capable mining spacecraft, that can deal with these Olympic swimming pool volumes and ISS masses, will not be small and will almost certainly involve on-orbit assembly. The late 2020s are a plausible time horizon for testing smaller scale asteroid mining spacecraft.

4.6. On-orbit construction

Beyond the scale on which components can be delivered from the ground and then assembled, construction on-orbit is required. That is, manufacturing components in space from raw materials. Commercial pressure for large structures to handle mining operations at asteroids or beneficiation operations in cis-lunar space (i.e. within the Earth-Moon system) will tend to lead to the development these capabilities.

Astronomy has plenty of potential for making use of large structures in space. Some examples are occulting starshades, radio dishes, support structures for shorter wavelength telescopes, interferometer trusses (up to some scale at which free-flying station-keeping satellites are more appropriate) and, ideally, large short-wavelength optics.

Plans for in-space construction are very limited at the present. An example of what might be possible on a usefully short timescale is the “SpiderFab” concept from the company Tethers Unlimited.⁷³ SpiderFab would build low mass carbon-fiber trusses in space.⁷⁴ At the planned rate of 3 m/hour several SpiderFabs working in parallel may be needed to build large (~100 m class) structures on a reasonable timescale. This effort was funded in 2015 by NASA’s Small Business Innovation Research (SBIR) program.⁷⁵ The

company is targeting the “early 2020s” for in-space tests, if all goes well.

The left over tailings from asteroid mining could become a major resource on the 2035 timescale. There will be strong incentives to contain the tailings from mining activities. First because clouds of fine particles from mining must not be allowed to collect around the mining spacecraft, shorting out electronics, reducing solar power yield or jamming moving parts. Second, if allowed to be free the tailings will stretch out along the asteroid orbit creating new meteor showers for Earth but also threatening satellites in Earth orbit. So for both mining and liability reasons the tailings must be contained. Tailings are at least 90% of the mass of the asteroid. They can slowly be sent back to a high Earth orbit at small incremental cost. Once they arrive they will provide construction materials in the 10,000 ton range that would cost trillions to bring from Earth. Building large equipment in space then becomes feasible.

However the timescale for these large construction activities is at least at the 2035 limit of the horizon considered here. Space agencies could hasten the arrival of this capability by funding efforts in this direction, including in-space tests at the ISS or elsewhere.

4.7. Rapid solar system transit times

Transit times for reaching space resources and returning them to where they will be used have a big effect on the return on investment (ROI) for commercial operations because of the “time is money” imperative. The need to move large masses (1000s of tons for water, 10s of tons in the alternate case of precious metals not discussed here) rapidly from asteroids at AU-class distances⁷⁶ implies more powerful rocketry than we now possess.

The ARM mission is a pathfinder in this direction. ARM (see Section 4.2) scales up SEP by a factor ~5, from ~8 kW for today’s GEO communication satellites (comsats) to ~40 kW. A similar scaling from ARM to ~200 kW is being considered by NASA for Mars missions⁴³ (Section 4.2), and does not appear to be a major stretch. Solar- and nuclear-electric (radioisotope) propulsion at 250 kW has been studied for Mars missions [26]. Electric propulsion can move ~150 tons from LEO to Mars orbit. The journey takes 3.7 years, though, and so is for cargo only. Spiraling out of LEO to Earth-escape and down to Mars orbit takes most of that time, with the transit to Mars taking only 1.7 years. Systems assembled in high orbit, e.g. at Earth-Moon L1 and fueled from lunar or asteroid resources can avoid the spiral-out phase; rendezvous with an asteroid using only SEP or NEP will be lengthy, so hybrid systems using chemical propulsion for rendezvous may be called for.

Based on ARM, NASA has based the “split mission” concept for journeys to Mars on a scaled up, ~200 kW, version of the ARM SEP.⁷⁷ Supplies would be sent to Mars orbit, or to Phobos or Deimos, using SEP in advance of the human crew. At the moment these plans use the Space Launch System (SLS) to launch the cargo mission, but a shift to on-orbit assembly and fueling is quite possible if those capabilities progress rapidly. Steps toward developing the advanced SEP for such missions will likely have begun by the mid-2020s and will facilitate both asteroid mining and planetary science.

For Solar System science much smaller payloads of only a few tons need to be delivered. But high power propulsion is essential. With only 15 kW of solar or radioisotope electric propulsion a Uranus orbiter mission still has a daunting 13-year journey out [27]. Clearly a 200 kW-class electric propulsion mission would arrive sooner, but studies are needed to know how just much.

A more distant prospect is to use nuclear fission-powered

⁷⁰ NuSTAR: <http://www.nustar.caltech.edu/page/about>.

⁷¹ <https://www.youtube.com/watch?v=vpVz3UrSsE4>.

⁷² SLS Program Mission Planners Guide Executive Overview: http://www.aiaa.org/uploadedFiles/Events/Other/Student_Competitions/SLS-MNL-201%20SLS%20Program%20Mission%20Planner%27s%20Guide%20Executive%20Overview%20Version%201%20-%20DQA.pdf.

⁷³ <http://www.tethers.com/AboutTUI.html#>.

⁷⁴ <http://www.space.com/28846-spiderfab-space-structures-incredible-technology.html>.

⁷⁵ <http://sbir.nasa.gov>.

⁷⁶ 1 AU = mean Sun-Earth distance ~150 million km.

⁷⁷ Gates, M., 2015, http://www.lpi.usra.edu/sbag/meetings/jul2014/presentations/0900_Wed_Gates_ARM_activities.pdf.

Table 3

Potential Commercial Space Activities in 2030 and their implications for astronomy and planetary science.

Commercial space activity	Effect	Value to astronomy, planetary science
Private Space Station in HEO	LEO-HEO transport	Servicing in ES-L2 Fueling capability On-orbit assembly
Lunar Resources	Large masses of water in HEO Major operational capability on lunar surface.	Fueling interplanetary/Mars missions in HEO Lunar far-side radio telescopes. Far-infrared lunar telescopes.
Asteroid Resources	Assembly of large mining equipment in HEO High power SEP/NEP Large masses of water in HEO Cheap construction material from tailings	Fuel for interplanetary/Mars mission in HEO Short journey times to Outer Solar System Large masses to Inner Solar System, including Mars Large on-orbit construction

rockets [28]. In a way space is the ideal place to use nuclear reactors; interplanetary space is already heavily irradiated by the solar wind and by Galactic cosmic rays, so our activities will not have any significant effect on that environment. Until asteroid mining becomes a major industry with political clout the substantial regulatory hurdles against using nuclear reactors in space are not likely to be overcome.

NASA is out in front on faster transit with its ARM and Mars plans. The need to limit Mars-bound astronauts' exposure to radiation, primarily against Galactic cosmic rays,⁷⁸ will keep the issue high on NASA's list of priorities. If encouraging the harnessing of space resources were given to NASA as a priority then they could do even more.

It seems safe to say that this class of Solar System rapid transit will arrive no earlier than the end of the time horizon being considered in this paper.

4.8. The potential state of play in 2030

An overview of the possible developments in commercial space in the 2020–2030 decade that have been discussed in this section is given in Table 3.

The effect that these developments will have on our in-space capabilities and so on astronomy and planetary science are also listed there. On this timescale there is of course great uncertainty about how far these gains will have progressed. The consequences for science will most likely be just beginning rather than fully realized.

5. Non-technical issues

Not every issue facing astronomers and planetary scientists is technical. A few of the non-technical issues are discussed briefly below. They are not easy to solve, but need to be stated so that we can begin to consider how to address them.

5.1. Timelines

All extrapolations such as the ones above are fraught with uncertainty. Especially in space ventures all dates have a tendency to “slip to the right”, sometimes by 5–10 years.

Nevertheless section 3 seems to show that it would not be prudent to ignore the potential near-term effects to about 2020 that commercial space resource exploitation could have on astronomy and planetary science.

The longer term changes to about 2030 discussed in section 4 are evidently more speculative, but bear following carefully as their potential impact is greater than the near-term changes.

5.2. Adaptation

Once the technical solutions exist to build lower cost missions there will remain the significant issue of convincing space engineers to adapt to these approaches. Decades of experience focused on minimizing mass have led to a large knowledge base for this approach. Abandoning this expertise in building finely crafted bespoke spacecraft in favor of simpler, low complexity, batch produced spacecraft will not be done lightly. In order to transition to the new paradigm the profession will need some incentive. Materially, the incentive will be the danger of going out of business if any other satellite builder adopts the approach. Intellectually and emotionally the incentive will be that, instead of repeatedly solving essentially the same problem, space engineers will at last be able to move on to new problems. A large number of these are implied in this study: LEO-HEO transport; HEO laboratories and habitats; space mining equipment, both lunar and asteroid; lunar surface to orbit transport; high power SEP/NEP rockets; fuel depots and on-orbit refueling. These are surely more interesting, and potentially more profitable, problems to solve.

Achieving low cost missions involves using a novel cost model. Adopting a new cost model is a big and risky step when a flagship mission is at stake. NASA and the other space agencies will rightly demand convincing evidence that this new approach is both truly cheaper and will deliver reliable spacecraft. The probable path is that commercial satellites will first demonstrate that the approach works, and the industry will have suitable spacecraft ready for purchase. Space agencies will likely then try out the approach on medium-class missions first, before committing to building flagship missions this way. This approach would delay the gains for astronomy and planetary science, but would make them more certain in the longer run.

5.3. Temptation: avoiding the ‘one big mission’

For any scientist the temptation will be strong to use any savings on launch and spacecraft to create an enhanced science payload: “Payloads grow to fill the budget available”, you might say. This is the easy approach. Discipline will be needed to restrain the scientists from spending all the gains on more payload rather than on a second flagship. This may be a discipline mandated by the space agencies, or it may be a self-imposed discipline based on a community consensus that more missions are better than one.

A large number of missions are better than one giant mission. (Each one, of course, still needs to be a big step over its predecessor.) There are several arguments for this position. First, a single large mission is a risk to the program. If it fails, there is no back-up. Second, the science of one mission cannot span the requirements of the field as a whole and the synergy we now have will thus be lost (Section 2.2). Third, but equally important, is that a diversity of missions is also a good for the intellectual vitality of the field. If all astronomers use just one telescope, this will limit the breadth of their scientific imagination. Scientists dependent on being granted

⁷⁸ Wilson, J.W. et al., 1998: <http://www.cs.odu.edu/~mln/ltrs-pdfs/NASA-98-mrsfm-jww.pdf>.

time on a single telescope feel a pressure to go along with current fashions in what questions and approaches are important. Time assignment committees tend to be made up of those who were successful in earlier rounds, reinforcing this narrowing trend. These effects will tend to restrict creative new approaches. Exoplanets are an example of how the ability of small teams of astronomers to take a different path led to an explosion of new science utterly unanticipated by the large majority of astronomers [29].

Sociologically it is harder to push for multiple diverse missions than for one giant mission. A giant mission proposal tends to accrete a large number of scientists and a single large community speaks louder than several smaller ones.

Politically it is also hard to “sell” a list of excellent missions both to the space agencies and to the governments that will pay for them. Saying these are the “two best” missions has intrinsically less force than saying this is “the best” mission.

The astronomy and planetary science communities should actively consider and debate these issues.

6. Conclusions

The timeline for the next large space observatories reaches out to 2030–2035. For the past 3 decades astronomers and planetary scientists have not had to think much about how space technology would change within their planning horizon. However, this time around enormous improvements in space infrastructure capabilities and, especially, costs are likely and can be anticipated in reasonable detail. Thanks to a new commercial focus for space ventures, substantially cheaper launchers will be the norm by 2020. Lower cost launch will lead to more massive and much cheaper, “off-the-rack” spacecraft. Also by 2020 human activity in low Earth orbit is likely to grow with privately run passenger vehicles both for tourism and to service commercially-run milli-gravity research laboratories. Biotech companies are likely to be major customers of these laboratories. On-orbit servicing of observatories can then return at a reasonable cost. Lunar landers and “interplanetary cubesats” can allow a new approach to planetary science.

The result of these changes will be that flagship missions could be proposed to the US 2020/2021 Astronomy and Planetary Science decadal reviews that cost a fraction of their present multi-billion dollar price tags. We can then have a full complement of well-matched “Greater Observatories”, spanning the whole of the electromagnetic, and now gravitational wave, spectrum. To achieve this result we must consider how to resist letting our aspirations expand to telescopes that cost as much as at present. This is, admittedly, a continual struggle.

Of course, the timeline I have presented may be too optimistic. Conversely, profit is a powerful motivator. Events may move swiftly if large profits are anticipated or realized. Scientists should be prepared.

Astronomers and planetary scientists would be well advised to include these developments in our planning, at least as contingencies. We should also urge our funding agencies to actively engage with the consequences of these developments and to help make them happen. “Only begin!”, as Goethe did not really say.⁷⁹

⁷⁹ The English lines attributed to Goethe in the Prelude in the Theater of Faust are: “Only begin! What you can do, or dream you can, begin it; Boldness has genius, power and magic in it; Only engage and then the mind grows heated; Begin, and then the work will be completed”. (e.g. https://books.google.com/books?id=gwoWAAAAYAAJ&pg=PA108&lpg=PA108&dq=%22only+begin%22+goethe&source=bl&ots=K16fcQb5z1&sig=M8iOxFSyqD1dg5_jis2j4PoFTI&hl=en&sa=X&ved=0ahUKEWjuyaGTo9LLAhXHHd4KHbYuDlQ6AEIjzAC#v=onepage&q=%22only%20begin%22%20goethe&f=false). This is wonderful, but is at best a very free translation (<http://german.about.com/library/blgermyth12.htm>).

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Space development and space science together, an historic opportunity

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ABSTRACT

The national space programs have an historic opportunity to help solve the global-scale economic and environmental problems of Earth while becoming more effective at science through the use of space resources. Space programs will be more cost-effective when they work to establish a supply chain in space, mining and manufacturing then replicating the assets of the supply chain so it grows to larger capacity. This has become achievable because of advances in robotics and artificial intelligence. It is roughly estimated that developing a lunar outpost that relies upon and also develops the supply chain will cost about 1/3 or less of the existing annual budgets of the national space programs. It will require a sustained commitment of several decades to complete, during which time science and exploration become increasingly effective. At the end, this space industry will be capable of addressing global-scale challenges including limited resources, clean energy, economic development, and preservation of the environment. Other potential solutions, including nuclear fusion and terrestrial renewable energy sources, do not address the root problem of our limited globe and there are real questions whether they will be inadequate or too late. While industry in space likewise cannot provide perfect assurance, it is uniquely able to solve the root problem, and it gives us an important chance that we should grasp. What makes this such an historic opportunity is that the space-based solution is obtainable as a side-benefit of doing space science and exploration within their existing budgets. Thinking pragmatically, it may take some time for policymakers to agree that setting up a complete supply chain is an achievable goal, so this paper describes a strategy of incremental progress. The most crucial part of this strategy is establishing a water economy by mining on the Moon and asteroids to manufacture rocket propellant. Technologies that support a water economy will play an important role leading toward space development.

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1. Introduction

Because of recent technological advances it has now become practical and affordable to establish a complete, robotic, industrial supply chain in space, enabling great science while promising tremendous benefits back on Earth [1]. Some of the benefits (mostly in space) occur in the early phase of establishing this industry, while more dramatic benefits occur after it becomes self-sufficient so that no further material need be launched from Earth and it can be scaled-up to great throughput. In this paper the end-state shall be called a Self-sufficient Replicating Space Industry, or SRSI. The main challenge for this concept is neither technology nor cost but simply convincing people it is realistic. In the 1970s Gerard K. O'Neill proposed orbiting space colonies, each

with 10,000 residents who would manufacture solar power stations to beam clean energy to Earth at a profit. Senator William Proxmire said of the concept, "It's the best argument yet for chopping NASA's funding to the bone. As Chairman of the Senate Subcommittee responsible for NASA's appropriations, I say not a penny for this nutty fantasy ..." [2]. Likely, many people will have the same reaction to a program of bootstrapping SRSI.

To be pragmatic, we may consider this to be a three-stage program as shown in Table 1. Stage 1 is not a formal program but rather the combined activity of the space development community (both inside and outside government). It includes activities that (1) contribute to space industry, (2) can be justified on their own economic merit and therefore funded by whatever means are available, public or private, and (3) help convince policymakers to embrace SRSI. A strategy for Stage 1 activities is discussed toward the end of this paper. They contribute to space industry by maturing the necessary technologies, by establishing infrastructure

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Table 1
Three stages of space industry.

Stage	Economics	Leadership	Goals	Duration
1	Each activity justified on its own merits	Amorphous	1. Make incremental progress in technology 2. Lower cost of operating in space 3. Convince policymakers to fund SRSI	Until leaders are convinced
2	Focused, multi-decade investment	Coalition of Nations	Intentionally bootstrap SRSI	2 to 4 decades
3	Payback of prior investments	Coalition of Nations	Benefit from SRSI	Perpetual

in space that lowers the cost of operating in space (so then Stage 2 can be accomplished for less cost), by demonstrating to policymakers and the public the many benefits of space industry, and by building conviction among policymakers that the SRSI concept is feasible. The robotics revolution already occurring in terrestrial industry will also help show that SRSI is feasible. Ideally, Stage 2 would begin today. There is no reason to have Stage 1 except for the fact that Stage 2 is not yet funded, so we must take practical steps to help convince policymakers to begin Stage 2.

A model showing how Stage 2 can be done affordably was presented by Metzger et al. [1] and will be briefly summarize here. We now know that the Moon and Near Earth Asteroids have all the raw resources necessary for an industrial supply chain (e.g., lunar ice containing hydrogen, carbon, and nitrogen, and the regolith containing silicon, metals, and calcium) [4–10]. Space industry can robotically mine these bodies for robotic manufacturing, beginning by making those materials that are easiest and require the least infrastructure to produce. For example, it can mine water for propellant and make crude metal from lunar regolith for building structures. Over time the industry can expand by receiving additional hardware from Earth at the same time that portions of the hardware are being made in space. The industry works to broaden its capabilities until it makes all the materials and parts in space, having developed a complete supply chain. Stage 2 should only take a few decades given adequate funding.

Stage 3 begins when space industry no longer requires imports from Earth and it becomes sufficiently autonomous that it no longer requires teleoperators to control every machine, so it can be loosely supervised and directed to grow exponentially without much further expense. At that point it becomes capable of making things of great value, both to enable in-space objectives and to return benefit to Earth. Its exponential growth will be rapid so it can begin providing large-scale benefits by the middle of the century. When teleoperation is no longer so important, the majority of space industry can be relocated to the asteroid belt where the greater accessible resources of the inner solar system are located. It can then extend its support of human activity to the outer solar system, and it can support even larger objectives such as terraforming Mars [11,12].

Ethical objections have been raised against space development, but others are claiming it is an ethical imperative. James S.J. Schwartz [3] has considered these positions and argued that (1) space development does not have a strong moral force behind it because it is unlikely to improve human welfare except in the far future, and (2) it will disrupt the efforts of space science, which actually does have strong moral force behind it. Therefore, he concludes that government should not change the legal and regulatory environment in ways that would help space development succeed. I will argue that both of his points are incorrect and that helping space industry to succeed should be a high priority. Although there have always been instances of development and science conflicting, we should ask whether the primary relationship between economic development and science has been one of

conflict of one of mutual support. I agree with some additional concerns that Schwartz raised about commercial space development. For example, if asteroids have trillions of US dollars of value, then commercial asteroid mining could increase the disparity between rich and poor. I will argue that there is a large and necessary role for government in the bootstrapping of space industry. Thus, this concern can be mitigated.

The paper is organized as follows. Section 2 will discuss how robotic technology is changing the prognosis for starting a supply chain in space. It will argue that the technological barriers to SRSI are in the process of falling away and that there is no reason to delay Stage 2. Section 3 develops a rough cost estimate. It argues that the cost is low so again there is no reason to delay Stage 2. Section 4 discusses the scientific benefits of space development. It also considers how robotics technology is changing the discussion about humans performing space science missions versus just robots alone. I argue that when space development is considered there is a very strong argument for humans. Section 5 will discuss the potential economic, environmental, and existential benefits of SRSI. Section 6 will discuss a strategy for Stage 1 to convince policymakers to embrace SRSI. Section 7 is a summary with conclusions.

2. Technological readiness for space industry

By the end of Stage 2, robots must be capable of all mining, manufacturing, construction, and associated tasks with minimal intervention by human teleoperators. With inadequate autonomy, the industry will be constrained by the cost of human labor and cannot be scaled-up to provide the greatest of the envisioned benefits. Robotics is not sufficiently advanced yet, and this may be seen by some as a large risk indicating that we should not start the project. However, robotics is already more than adequate for the early stages of space industry, and that will provide immediate scientific benefit as discussed in Section 4 while improving the cost effectiveness of space exploration. The robots can start as fully teleoperated from Earth¹ while they are few in number. Even before going to the Moon, each new piece of industrial hardware will be proven on Earth through field tests at lunar analog sites. Once on the Moon, they can be operated in the presence of a lunar outpost so astronauts provide additional troubleshooting and insight. Humans are not strictly required but will make it easier and faster to start the industry, which is important because the benefits will be obtained sooner. Furthermore, we have scientific reasons to put astronauts on the Moon [13], and the nascent industry will provision the outpost with oxygen, water, and spare parts, making it affordable and increasing its scientific value. As the lunar supply chain is bootstrapped and diversified, robotic advancements discussed below will allow us to increase the ratio of robots to human

¹ The 2.7 s or less round-trip communication delay is manageable for many tasks, but robots will need some degree of automation for fine tasks.

teleoperators. This trend will make the labor cost stay reasonable throughout the process. Within a few decades as robotic artificial intelligence matures, the teleoperators can adopt a loose supervisory role over the robots and the industry can grow exponentially. There is nothing to suggest we should wait for robotic autonomy to improve before we start the project.

According to Bill Gates in 2007, robotics “is developing in much the same way that the computer business did 20 years ago” [14]. Terrestrial industry has been slow to adopt automation, so the factories on Earth do not give a true picture of what is already possible. For example, less than 8% of transportation tasks in the U.S. are automated although 53% could be right now [15]. Widespread adoption of automation is expected to begin this year because cost is dropping steadily even while capabilities are increasing, including the interpretation of 3-dimensional vision and ability to work in unstructured environments. A 2016 review finds “robots dexterous enough to thread a needle and sensitive enough to work alongside humans. They can assemble circuits and pack boxes. We are at the cusp of the industrial-robot revolution” [16]. The sectors most needed for space industry are also the most automatable: manufacture of computers and electronics, electrical equipment, components, appliances, transportation equipment, and machinery are at least 85% automatable today [17]. Sectors that are not as important for the early stages are the ones that need more progress, such as wood products, paper, food, and textiles.

Not just manufacturing, but other industries are converting to robotics. Refineries and chemical plants have long used automation in their process control systems. Mining companies are now adopting fully autonomous vehicles for underground mining, dozing, and hauling [18,19]. Robotics is penetrating the construction industry, as well. Masonry buildings are constructed by robots that lay bricks three times as fast as humans [20]. Robotic systems are being developed to autonomously construct steel beam buildings, including high-rise buildings [21].

Other than maturing the robotics, the technological progress most needed for space industry is to adapt existing technologies to the space and planetary environments. This is already on-going, including mining vehicles [22,23], low-gravity regolith conveyance systems [24,25], beneficiation systems to concentrate minerals found in lunar regolith [26,27] and chemical processors to extract resources from the minerals [28–30]. Their maturity level is adequate for the beginning stages of industry, and the point of bootstrapping is to develop the technology as we go along. Therefore, we can begin now.

Integrating the many machines and activities into factories will be challenging, but systems engineering methods were developed to handle this and they have a long history of success. An example is found in this fully automated factory in Japan:

At this moment, in one of Fanuc’s 40,000-square-foot factories near Mt. Fuji, robots are building other robots at a rate of about 50 per 24-h shift and can run unsupervised for as long as 30 days at a time. When they stop, it’s because there’s no room to store the goods. Trucks haul off the new robots, the lights are cut, and the process begins anew. “Not only is it lights-out,” says Fanuc vice president Gary Zywiol, “we turn off the air conditioning and heat too” [31].

Since then, more “lights out” operations with only robots, no humans, have been established including machine shops, distribution centers, and factories making things as diverse as food and electronics [32,33]. The extensiveness of automation is described

for a 2015 Chinese factory that makes cell phone modules:

... all the processes are operated by computer-controlled robots, computer numerical control machining equipment, unmanned transport trucks and automated warehouse equipment. The technical staff just sits at the computer and monitors through a central control system [34].

Integrating the machines is becoming less complicated as robotic intelligence improves so the work environment can be left unstructured and the robots will figure out how to interact on their own. A helpful way to discuss it is by referring to Hans Moravec’s four phases of robotic intelligence [35]. These correspond to (1) basic sensory perception and manipulation tasks (“lizard-like” robotics), (2) learning on its own through experiences in the real world (“mouse-like”), (3) maintaining a mental model of the world so decisions can be based on assessment of outcomes before doing them (“monkey-like”), and (4) general intelligence including the power of abstraction (“human-like”). In factories with thoroughly structured work environments like the lights-out factories that already exist, only lizard-like robotics is necessary. However, already by 2011 inexpensive workstation microprocessors [36] surpassed the 100 Giga Instructions per Second (GIPS) mark in computing power that Moravec estimated is necessary for mouse-level intelligence.

The software to take advantage of this hardware power is also making great strides. “Lizard-like” perception capabilities are routinely designed into robots using a wide variety of sensor systems, enabling them to perform more complex tasks in unstructured environments and even to interpret human intention [37,38]. Mouse-like learning is now becoming reality, as well. Deep learning (where layers of simulated neurons are trained in a process mimicking human learning) is having remarkable success [39]. Platforms like Facebook use facial recognition developed through Deep Learning techniques, with error rates dropping by 25%–50% year-by-year so it is now 96.4% accurate [40]. While factory robots in space do not need facial recognition, the point is that deep learning works as a method and eliminates the need to design software algorithms for complex tasks. Factory robots in unstructured environments will need to identify objects they encounter, and programming that capability would be a terribly difficult task, if not impossible; deep learning has already enabled robots to visually identify objects from among 1000 categories, and progress is ongoing to identify objects from among 10,000 categories [41]. Deep Learning also improves efficiency of factory tasks. It is enabling robotic welders to continuously improve by watching their welds through cameras [42]. Other factory robots are teaching themselves new tasks such as picking objects they have never seen before out of a bin. A robot is told generally what to do without being told how, and after one night of self-guided practice it can perform the task as well as if an expert had programmed it [43]. Then, the factory robot instantly transmits what was learned into the neural networks of all the other robots in the factory [43,44]. The sudden progress in robotic learning suggests we may have mature mouse-like robotics before 2030, the date Moravec predicted [45], so designing the SRSI machines to work together will not be so difficult.

3. Cost of space industry

Technology is not a barrier to beginning Stage 2, so next we consider whether there is a cost barrier. Unfortunately only a few

rudimentary studies of SRSI have been performed and they are not adequately detailed to inform a good cost estimate, but we must bound the cost as well as we can using those studies.

The first study [46–48] was done in 1980 and concluded that 100 tons of factory hardware needed to be sent to the Moon to initiate SRSI. That was for only 80% closure (meaning 20% of the mass of a newly fabricated factory would be sent from Earth in each reproduction cycle), so a factory with 100% closure would need more diversification of manufacturing processes and thus would be more massive. The concept has also been studied for starships that travel to other solar systems then replicate [49], so 100% closure would be required, and a 2004 study considered it again for the Moon [50]. Unfortunately, landing 100 tons or more of hardware on the Moon is expensive, the troubleshooting to make it work all at once would be overwhelming, and the technologies are not available yet for a complete supply chain in space. If we have to do it all at once, then we cannot get started. This is where the concept of bootstrapping comes in: instead of launching 100 tons of factory hardware, we can build it up over time using mass that is already in space. Similarly, when settlers moved to a new continent, they did not carry entire factories from their homeland across the ocean. Instead, they built up native industry over time utilizing local materials. Metzger et al. [1] modeled this strategy to see if it can result in a net reduction of launch mass. The model suggested that it can: only 12 tons of assets and parts landed on the Moon over the span of few decades resulted in 150 tons of factory hardware at completion. Thus, it suggested a better than 10:1 reduction in launch mass might be achieved. The model also suggested that if 42 tons of assets and parts were landed, then the industry could have up to 100,000 tons of assets at the end of the same period, indicating better than 20,000:1 reduction; so it is non-linear. The modeling was simplistic and only intended to demonstrate the concept to motivate a larger study, which has not yet been funded. Bootstrapping also spreads the cost over a longer time, allows us to get started right away, matures the technology in the same environment where it must operate, and provides immediate scientific benefits by provisioning outposts or other activity in space. Since we were going to do many of those other activities anyway, they help defray the startup cost.

To make a very crude estimate of Stage 2, we note the cost of International Space Station (ISS) was about US \$150 billion [51], and it consists of about 420 tons of hardware [52] so the rate is US \$360 million per ton of human-rated systems delivered to Low Earth Orbit (LEO). The gear ratio to the lunar polar region is about 4 [53], meaning that for every ton to be landed on the Moon about 4 tons must be launched to LEO. Therefore, 12–42 tons to the Moon's surface requires about 48–168 tons to LEO. This suggests that if the hardware were given the same pedigree as human-rated systems it would cost between US \$17 billion and US \$60 billion. Spread over three decades, that is US \$0.57 billion to US \$2 billion per year, about 3%–12% of NASA's budget, or 2%–7% of the space budgets of the ISS partner nations. However, the hardware for space industry need not be human-rated, it will be based on existing terrestrial factory technology, and much of it will be copies of the same parts for many identical robots, so the development cost should be far less than this estimate predicts. Also, the launch costs using expendable rockets will be much less than the human-rated Space Shuttle. It is highly desirable to do the bootstrapping in the presence of a lunar outpost. Without that, the idealized model of Metzger et al. [1] may prove far too simplistic as hardware fails and there are no humans to troubleshoot and repair it. (This is discussed further in Section 4.3.) It is difficult to constrain how far off that model could be, but instead I will assume this project does take place at a lunar outpost. Spudis and Lavoie [54] studied a lunar ice mining outpost that supports two to four crewmembers and

utilizes the ice resources to lower its own cost. The study included the development of all transportation vehicles except launch vehicles from Earth. They estimated² the total cost of the program would be US \$88 billion in 2010 dollars, with a peak annual cost of \$6.65 billion in year 13 of the 16 year program. Assuming worst-case that this peak level is constant and perpetual until SRSI is established so the human presence can grow as industry grows, then the cost of an outpost would be about 22% of the civil space budgets of the ISS partner nations for a total cost (outpost plus industry hardware development) of less than 30% of the combined civil space budget.

The costs are very low compared to the benefits. The primary barrier is neither technical nor economic, but just the feeling that it is a “nutty fantasy”, so this is why we are in Stage 1 for now. A cost estimate of the possible activities in Stage 1 is beyond the scope of this paper, but the idea is that each step is commercially profitable and/or makes the national space programs more cost-effective so the space agencies will fund them from existing budgets. Stage 2 is where the intentional bootstrapping of SRSI begins, requiring sustained investment for several decades as estimated above. The investment toward SRSI beyond the cost of the outpost alone will produce increasing benefits for the outpost, including the ability to manufacture spare parts, build new experiments or tools, and construct radiation shields over habitats. However, it may not pay back the entire marginal investment until Stage 3, defined as the point where space industry becomes self-sustaining. It is beyond the scope of this paper to estimate the economic value of those benefits because a larger study is required. However, the following sections will generally describe some of the benefits in Stage 2 and 3.

4. Scientific benefits of space development and SRSI

4.1. Direct benefits for space science

Other articles in this special issue discuss specific ways that mining and manufacturing with space resources will make space science more effective. These include making rocket propellant from asteroidal or lunar volatiles, building radiation shields and landing pads from regolith, providing breathing oxygen and water for outposts on the Moon or Mars, and processing regolith to make metal for 3D printing spare parts. These activities will make space missions more effective because they reduce the amount of mass that must be launched from Earth while providing more flexibility during missions to respond to problems. The ultimate fulfillment of this is to build SRSI so that only humans need to be launched from Earth, something Mason Peck (former NASA chief technologist) dubbed “Massless Exploration” [55]. The full supply chain could then build entire spacecraft and a transportation network for scientists to visit bodies throughout the solar system. It could build grand astronomical observatories in space like the one described by Seth Shostak consisting of many electronically linked telescopes orbiting the sun, which could see a small automobile on the surface of an exoplanet 100 light years away [56]. It could build a planetary-sized particle collider on Mercury driven by solar energy to probe physics at levels we cannot currently dream of exploring, which might bring radical discoveries that benefit our civilization in ways we still cannot guess. Since SRSI can provide much greater leveraging of human labor than our existing economy, it can support any scientific activity (or artistic, literary, or other activity) we wish to explore by provisioning an institute

² They used NASA's accounting method then doubled the entire estimate [Paul Spudis, personal communication].

located somewhere in space.

4.2. General relationship of science and economic development

Schwartz [3] raised the concern that space development will disrupt space science and therefore (since he believes it will provide little benefit to humanity except in the distant future) we should not be eager to get it started. He wrote:

Let me first repeat that I have no in-principle objection to space development; my concerns arise when space development risks conflicting with space science ... Though I grant that few conflicts exist at present, as space development and science capabilities improve, so too will the chances that development and science activities interfere with one another

There is much viable science that can be conducted only prior to development—that is, before settlement or exploitation contaminates, disturbs, or destroys sites of scientific interest [3].

The problem with this objection is that it assumes we were actually going to do science at these asteroids or lunar sites before development could destroy or disturb them. If we were never going to investigate them anyway, then the argument does not work. Since 1991, humanity has sent spacecraft past 12 asteroids, about 2 years per visit. There are over a million asteroids larger than 1 km in diameter [57], and several billion over 10 m in diameter [58]. At the current rate of scientific investigation, we could visit them all in about 10 billion years, except the sun will not last that long. Mining will cause us to see far more than we would, otherwise. The same argument can be made for lunar mining, which may be largely underground to escape the radiation problem, and therefore will reach materials that would not otherwise be accessible for science, but which have immeasurable scientific value. This is also similar to our experience on Earth. Some subsurface exploration is funded for purely scientific reasons, but vastly more is funded for economic reasons, and the influx of data from economic geology has been a tremendous boon for science. The U.S. Bureau of Labor Statistics database shows that far more geologists are funded by economic activities than by pure science.³ We can expect similar trends in space. Economic planetary geology will fund thousands more scientists who will publish papers on the great influx of data coming from space mining missions, including samples from the mined asteroids and the Moon, telescope observations for prospecting, and theoretical modeling to understand which asteroids or lunar locations are better for mining.

Furthermore, scientific productivity is correlated to economic development. Gantman [59] studied the publishing record of scientists in 147 countries and found that scientific productivity correlates strongly (with high statistical significance) with the size of the country's economy measured by Gross Domestic Product (GDP) and with the development of the country measured by GDP per capita. The idea is that large economies have more money at their command to direct into scientific research, and developed countries afford scientists better access to the scientific equipment and infrastructure needed to perform the research [59]. The mechanism that makes this true country-by-country should also make it true for the world as a whole, as well as for the "country" we call space. As the global economy grows, more funding is available for science, and as civilization becomes developed, scientists have greater tools

and other resources at their disposal. When SRSI leverages human labor by another factor of 10 or more, we can expect GDP to increase so both funding of science and access to resources for science will improve. This will enable scientists to make even better use of the vast, new data sets coming back from the increased activity in space.

As argued above, the initiation of SRSI (Stage 2) can be accomplished for a minority fraction of the existing national budgets for space science and exploration. Therefore, if we were to gain no benefits from SRSI other than the scientific ones, it would still be worthwhile. The benefits to science will accrue not only in Stage 3, but also in Stages 1 and 2.

4.3. Relationship of human and robotic space science

The advances in robotics technology also change the discussion whether science and exploration should include human-tended (crewed) missions or only robotic missions. As robotics are becoming ever more capable, it is possible that a single robot may one day (perhaps soon) produce as much value per hour on a planetary surface as a human does while remaining far less expensive. This might intensify the questioning why we have humans doing science and exploration in space.

On the other hand, for space development activities there is a very strong argument for human spaceflight. At present, robots are not sufficiently advanced for troubleshooting and repairing other robots. Without humans present, when a mining or manufacturing robot breaks, operations at the manufacturing site may be stopped until a replacement robot is sent from Earth. These failures can be expected frequently because terrestrial technology in these fields has not yet been well-adapted to the lunar environment, and because these activities require greater ruggedness than robots just scientifically sampling. Furthermore, we will probably have difficulty identifying the root cause of hardware failures or operational problems on the Moon, so without humans on-site the replacement robots may exhibit the same or related failures multiple times before an adequate diagnosis is made. Humans are uniquely capable of performing these tasks at a lunar outpost. Thus, with humans present, advances in space development can be far more rapid than by purely robotic space development activities alone. This means the great scientific benefits of space development, as well as the economic and environmental benefits discussed in the next section, will begin to accrue much sooner. Because SRSI in Stage 3 grows exponentially, the benefits will also accrue exponentially. The difference between an exponential curve and a delayed exponential curve diverges to infinity. This suggests that the human contribution in space development missions is an immeasurable value per dollar cost. This model is too simple but it illustrates the point that value compounds geometrically in development missions, which changes the calculus for human spaceflight. Knowing how SRSI may help solve the world's economic and environmental problems, the public may have much stronger support for a lunar outpost if the astronauts spend a portion of their time standing up lunar industry.

Human presence in space is also made more economical in a space development scenario and this contributes to the reasonableness of human spaceflight. As Spudis and Lavoie have demonstrated [54], a lunar outpost based upon the use of lunar resources is less expensive than one in which everything is launched from Earth. Robots and humans will be highly synergistic in Stage 2, and in Stage 3 the robots will build spacecraft and outposts that open the solar system for humanity.

³ It shows that 65% of geoscientists are working in mining and other economic fields, 18% in research (some of which is economic research and some is pure science), 12% in government (mostly managing economic activities), and only 5% in academia (some of that is teaching and some is scientific research).

5. Economic, environmental and existential benefits

The economic, environmental, and existential benefits are more speculative since we cannot tell what will change several decades in the future. I wish to emphasize that we have strong justification for space development whether or not we are sure to gain these additional benefits. There are at least two reasons for this. First, space development is already justified by the scientific benefits. Since we are already spending money in space, and since the existing budgets are adequate, then the most effective use of those funds should be pursued, and that includes space development. Second, the humanitarian and environmental challenges discussed below do not have any completely sure solutions, either terrestrial or space-based. As long as space development provides at least some significant, additional chance of solving them, then there is an ethical burden to pursue that chance.

5.1. Economic and environmental benefits

Economic and environmental benefits are linked and will be assessed together. The benefits may include materials and manufactured goods sent to the Earth from space, space-based communications systems and computing linked to Earth by those communication systems, and space-based power beamed to Earth.

5.1.1. Minerals and manufacturing

Civilization and the industry that drives it are stressing the planet in a number of ways, including exhaustion of the most enriched deposits of some economically important minerals [60–64]. This will be exacerbated by our economy expanding to provide developed economies to all 7 billion people, soon to be 11 billion [65,66]. Some of these minerals are important to renewable energy and the shortage threatens our ability to scale-up renewable energy to global levels [67–69]. Mining in space can help replace these minerals, making renewable energy and other important technologies more affordable [70–72]. Some manufacturing processes will also benefit from the space environment [73]. These benefits will begin early in space development, and as Stage 2 progresses into Stage 3 then it may become economic to bring a wider range of space-made goods and materials back to Earth.

5.1.2. Data and computing

Exponential growth is occurring in computing and the internet, and since it is exponential it can quickly reach physical limits. When communication channels reach their capacity then more spatial diversity is needed to transmit data in parallel. For example, more fibers must be laid across the oceans, or satellites must use narrower antenna beams so they can transmit to smaller spots on the ground side-by-side. Installing spatial diversity is expensive and becomes the limiting factor when costs are too high or no more diversity is possible. A recent meeting at the Royal Society concluded that a number of “capacity crunches” are looming [74]. The world population is increasing, the percentage using the internet is growing [75], 50 to 100 billion physical objects (in addition to the people) will be using the internet by 2020 [76], and individual users’ data rates are growing exponentially with a 50% increase per year for thirty years straight [77], which is analogous to Moore’s Law for transistor density. A 2015 report by the Semiconductor Industry Association and the Semiconductor Research Corporation says, “Unfortunately, neither existing technologies nor current deployment models will be able to support the skyrocketing demand for communication, especially in the wireless sector” [78].

Another issue is with the energy that computing uses. The semiconductor report [78] also estimates the growth of computing

in terms of binary bit transitions per year and the energy used for each one, including a physics-based theoretical lower limit, and this shows that if this growth were to continue then by 2040 our computing and the Internet would consume all the energy the world produces. That is only the operating energy for computers; the energy to manufacture them is far more, since for example the energy to manufacture just one memory chip exceeds the total energy to operate a laptop computer for three years [79]. Considering the manufacturing needed to support the growth rate of data storage and data transmission [78], global energy limits could stifle progress in computing well before 2040.

One possible solution is to offload the burden to space. Presently, data communication between Earth and space is far too slow for satellites to handle much of the internet’s traffic or to locate much of our computing off-world. This can change with space industry. First, SRSI can build large phased antenna arrays in orbit, large enough that beam widths can be very narrow. I calculate that for the antenna’s Fraunhofer region (far field) to begin at the distance to the Earth’s surface from geostationary orbit when operating at 38 GHz, the antenna would be 375 m in diameter and the beam spot would be 1 km in diameter on the ground. Since the United Kingdom has a land area of 243,610 km², about 243,610 beam spots would fit within the UK alone. This is about 4.6 times more than the number of mobile phone base stations (cells) presently in the UK [80]. Power densities at the ground can be kept lower than mobile base stations as needed for biological health, and antenna arrays on Earth can still receive the signals. With a Shannon Limit [81] of about 10¹¹ or 10¹² bits/s per beam, this would provide a data rate of 25–250 petabits/s for the UK, which is 20,000 to 200,000 times the entire average Internet rate of the UK in 2015 [82]. Spatial diversity can be increased further because these beam widths are a tiny fraction of a degree, so a single ground station with a phased array can receive channels from thousands of points around geostationary orbit, while each point in geostationary orbit transmits thousands of different channels simultaneously, each to a different point on the ground. Thus, microwaves alone have the potential to extend the UK’s Internet by a factor of 20 million to 200 million when we can build vastly larger antennas in orbit. Furthermore, SRSI could manufacture laser optical communication systems for even smaller beam spots, tighter directionality, and higher data rates per channel, although they would not work through cloud cover. The combination of both optical links and microwaves (to supplement during cloudy conditions) across the globe, with terrestrial fiber optics routing data that was diverted due to cloud cover, could vastly exceed today’s global Internet throughput.

With such a communication network, the bulk of computing can be located off-world, relieving Earth of the energy demands for both manufacturing and operating computers. Only the compressed data streams for user interfaces need be transmitted to and from the Earth. While space communications will have greater latency, there are techniques in conjunction with terrestrial networks and computing plus increasing artificial intelligence to make it acceptable. Since the in-space computers and network will be made by the autonomous SRSI, the cost will be very small. This will give humanity the benefit of much more computing than terrestrial energy and resources could ever provide, escaping the exponential limits of growth. This may be extremely important to our future.

5.1.3. Energy

Space industry could also move power generation off-Earth by building a Space-Based Solar Power system (SBSP) [83–86]. There is widespread belief, which I share, that it is presently too costly to launch SBSP from Earth to make it worthwhile [87] except for special applications where cost is not an issue. Solar cells located on

Earth's surface with batteries (to extend solar energy into the nighttime and cloudy days) can provide the same service more cheaply than a system launched from Earth into space. However, if we have SRSI, then building SBSP will be low cost since it will come from excess manufacturing developed through self-replication. Analogously, hunter-gatherer societies do not pay for the food chain to grow their food or building materials, because the food chain is self-replicating and autonomous from the human perspective. SRSI can be considered a designer food chain adapted to space. SBSP can beam carbon-free energy to Earth at far less than the cost of petroleum-generated power and far less than Earth-based solar energy with storage, so the predicted population of 11 billion people by 2100 [65,66] can live in developed economies without further environmental impact. With adequate energy we can solve other planet-scale problems, such as the shortage of fresh water, because energy can drive desalination plants, and we can begin reversing environmental damage.

Presently, if all humans worked as hard as agricultural laborers (about 0.1 horsepower = 0.074 kW [88]) then the 155.6 million laborers in the U.S. with 2000-h work-years would annually produce 23.4 TWh (0.084 exajoules, or EJ) of thermodynamic work toward goods and services using their muscles. That compares to 28,600 TWh (103 EJ)⁴ [89] of energy used annually by machines in the U.S. including oil, coal, gas, solar, nuclear, etc.⁵ This says that machines do greater than 1000 times more thermodynamic work than human muscles, so less than 0.1% of things made or services provided in the U.S. are actually through human labor, while more than 99.9% are by machines. The role of humans has largely evolved into controlling machines and making decisions. This roughly 1000-to-1 leveraging in developed nations and 300-to-1 in the global average is what makes possible the diverse supply chain, which in turn enables the existence of modern technology. Our ancestors would have considered smart phones and jet planes to be just as fantastical as O'Neill's space settlement was for Senator Proxmire. Sir Isaac Newton could not have built a smart phone even if he had detailed instructions because his world had not bootstrapped the extensive supply chain required for it, including energy sources that give us the productivity to operate that supply chain. SRSI can reproduce up to the limits of resources in the solar system, which are billions of times greater than the resources on Earth [90], without harming the ecosphere so it can increase our leveraging by a factor of 10, a thousand, a million, or more, broadening the supply chain, enabling further technological progress, and taking human civilization to a higher level.

5.2. Existential benefits

We cannot realistically deal with the existential threats of the solar system and galaxy without more leveraging than we presently have. With SRSI, we can begin seriously reducing those threats. SRSI can build enough spacecraft to survey all the small bodies of our solar system and build more spacecraft to travel to large numbers of them and adjust their orbits. It can put observatories throughout the solar system looking for dangers from beyond, and build robotic re-boot systems including genetic banks to restart life and civilization if disaster does strike. Microwaves from SBSP could power the world through the ash cloud of a supervolcano eruption when wind and solar energy sources would fail (causing more deaths

than the eruption itself), and it could rapidly grow and manufacture relief supplies in space and send robotics to the surface to ramp up factory agriculture. Many more such examples can be imagined.

We could also rapidly terraform Mars [11]. First, autonomous robotic labor can capture icy bodies in the outer solar system and transport them to enter the Martian atmosphere. Second, it can build SBSP in orbit around Mars, and it can build Mars landing spacecraft bringing materials and equipment to provision the initial factories on the surface of Mars. This may require SRSI to transport material from the Main Asteroid Belt. Third, powered by SBSP, the Martian surface industry can eventually become self-sustaining then self-replicate to grow exponentially, produce greenhouse gases, remove soil salts, and rapidly transform the planet. Fourth, the Martian surface industry can then metamorphically recycle most of itself and move underground to leave Mars beautiful. SBSP will continue to support Martian civilization. When Mars can support a large population with no reliance on Earth, then we are truly a multi-planet species. That will provide buffering against disasters that happen on only one of the two planets. Simply putting colonies on Mars will not achieve this, since the colonies will be dependent on Earth and Mars will remain a very inhospitable environment. Only scaled-up SRSI holds the potential to make us a two-planet species. A study should be performed to quantify how quickly this could be accomplished, but considering that SRSI could exceed a million times the economic activity of all Earth within this century, it may not be such a distant goal.

Finally, it can take humanity and other life beyond our solar system. It could initially build robotic ships to take SRSI-bootstrappers to other star systems where the robots can locate and terraform candidate worlds in advance of our arrival [91–93]. It can then bring humanity to those worlds by building multi-generational ships for us [94–97], or it can send genetic banks (embryo ships) to slowly populate those terraformed worlds [98,99].

These ideas are fantastical today because our supply chain is too narrow and our industrial leveraging far too small. SRSI will change that. Without SRSI, we have no reasonable possibility of significantly reducing these existential risks. If this were the only benefit to SRSI, we should still do it.

One additional benefit of SRSI that relates to existential threats is the possibility that artificial intelligence and robotics could destroy humanity. One possible approach to dealing with this is to perform research in these fields at a safe location off the Earth. SRSI can enable this by building the computer systems off-world at a chosen location. This is not a complete solution, but it may provide important tools to move forward in this field with greater caution. It should be noted that SRSI itself does not require general artificial intelligence; it only requires the level of automation that we are putting into factories on Earth today to perform simple tasks, and therefore it is not a threat by itself.

5.3. Objections

Before looking at objections, I should clarify that I am not claiming it is a provable fact that we can realize these economic and environmental benefits quickly enough to solve our present challenges. Instead, I am claiming there is a significant probability that space industry will help solve those challenges quickly enough, and it may turn out to be the only adequate solution, but if we do not attempt this solution then there is zero probability it will help. We cannot know for sure because the global challenges are complex. Also, I am not claiming the justification for space industry based upon these economic and environmental benefits needs to stand alone to be a valid reason to begin space industry (although I, personally, do believe they stand alone as valid). What I am arguing

⁴ 2015 total, reported as 97,523 Quadrillion Btu.

⁵ Much of that energy is not productive thermodynamic work because of theoretical efficiency limits and waste, but also the majority of U.S. workers use their muscles for productive thermodynamic work far less than agricultural workers. Therefore, this rough comparison is still valid.

here is that these benefits provide supporting justification for space development when considered alongside the benefits to space science. Space science is already supported globally at funding levels that are adequate to perform space development, and since space development will make space science more effective and therefore give the public a better return on its investment, any additional benefits we might gain from space development are serendipitous. The fact that this serendipity just might save civilization, with no downside for trying, makes it an easy sell. With this in mind we can address the following objections.

5.3.1. *Objection: terrestrial solutions are more likely*

One objection is to say that space-based solutions are not necessary because terrestrial technologies, especially nuclear fusion and renewables such as solar, wind, and geothermal, coupled with improvements in efficiency and sustainability, will probably solve Earth's energy problems. The weakness in this objection is that there are significant unanswered questions about these other technologies, so we do not know for sure they will provide solutions that are adequate or come quickly enough although the stakes are high. Furthermore, it is not an either/or decision. The global energy system may be most effective when it includes the synergy of terrestrial and space-based solutions together. One example is space mining that could provide necessary but increasingly scarce elements for renewable energy technology. A few of the specific questions about nuclear fusion and renewable energy are reviewed below along with ways that space-based solutions provide synergistic or alternative solutions.

One concern with nuclear fusion is that the world must transition away from fossil fuels as quickly as possible, both because more affordable fuels are expected to decline this century [100,101] and also because they add carbon to the atmosphere [102], but nuclear fusion might take too long to develop. The timeline of the world's leading fusion effort, consisting of the International Thermonuclear Experimental Reactor (ITER) followed by a demonstration reactor (DEMO), was planned for completion about 2050. An economic model based on historic trends says there will likely be three demonstration reactors in the early 2050s, ten operational reactors in the early 2060s, and 100 improved reactors in the 2070s, which will still provide only a small fraction of the world's energy at that late date [103]. The study says that after a brief period of exponential growth it enters into a linear growth phase. We would need to build 200 reactors *per year* in that phase to reach 30% share of the world's energy by 2100, and that assumes no further delays. In 2006 the plan for ITER was to achieve first plasma in 2016 [104], but it is now planned for late 2025 [105], slipping 9 years in 10 years, almost year-per-year, and the previous planning was declared "totally unrealistic" [106]. Considering the significant knowledge and technology gaps that remain [107–110], and that we do not know what we do not know, there is a risk we will again find our plans have been unrealistic. Some are even arguing that economic fusion is not a reasonable goal [111]. Space-based solutions can provide global scale energy on the same timeline or even sooner than fusion with arguably less schedule risk since no new physics are required. Because SRSI does not depend on the world's limited resources or labor force, it can scale-up exponentially while terrestrial energy solutions like fusion can only scale up linearly. Pursuing both paths simultaneously will give humanity the lowest total risk.

A second concern about nuclear fusion is that it may not be sustainable when scaled-up to global power levels. The fuels are sufficient to last millions of years, but some other elements needed to build and operate the reactors may not be [112], so we must develop alternative technologies that do not need those scarce elements (entailing additional technical and schedule risk beyond ITER and DEMO) or we must develop new, extreme extraction

methods to obtain those elements (entailing new technical risk, higher cost, and further possible damage to the environment [112]). The concern is that eventually "the cost of producing a further ton in terms of energy, water, and environmental damage will be so great, that mining will cease" [113]. Elemental scarcities may be relieved by space industry that mines asteroids and returns the "vitamin" elements back to Earth, thereby making fusion more affordable with less environmental damage, so there can be synergy between the two approaches. Also, after we have space industry then SBSP may be a less expensive energy supply in terms of ongoing costs, so fusion might be limited to more appropriate niche applications and the global supply of those elements will not become so stressed.

A third concern with fusion is that it is not perfectly safe [114] or environmentally friendly [115], so although it is vastly better than fission the politics could still turn negative. Although the risks are small, the risks from SBSP may be smaller since the microwave beam would have low power density [116,117].

A concern with switching from fossil fuels to the optimum mixture [118,119] of renewables like solar and wind (requiring a smart grid with storage and/or excess generation capacity, along with nuclear fission and/or fusion) is that it is expected to reduce the world's net energy return on energy invested (EROI) [120,121]. Roughly, EROI is the amount of energy that the energy sector produces per unit energy that it consumes. It is usually calculated for each energy source separately to compare their effectiveness. The EROI of petroleum has already dropped from greater than 100:1 in 1930 to less than 20:1 by 2005 [120] as the cheaper petroleum reserves have been progressively exhausted, and this may already be hindering the global economy [120,122–124] including the economic growth of underdeveloped nations [125]. Some argue that lower EROI is not able to support the flourishing of modern civilization because it does not provide adequate leveraging of human labor to provide the full breadth of goods and services we have grown to expect [126–129]. Lambert et al. [126] found that measures of well-being, including the percent of children underweight, female literacy, and rural access to improved water, correlate to the EROI in a society, independent of the per capita energy expenditure [130]. Those data show that the EROI necessary for a higher standard of living is somewhere above 20 to 30, higher than terrestrial renewable energy is capable of providing. In fact, they conclude,

Despite the best intentions of improving net energy balances for a developing nation, the large-scale introduction of renewable energy generation may have too low an EROI and may prove too expensive to facilitate continued growth in developing economies [125].

SBSP can overcome this potential problem because it has an extremely high EROI (solar energy concentrated by an autonomous system and put into a form requiring minimal energy expense by humans to capture it). It can be deployed at global-scales or just locally in developing areas for little cost on the ground.

Another concern is that the public and its leaders may not invest adequately to set up the terrestrially-based renewable energy system in time to avoid economic and environmental disaster. A 2014 study estimates the U.S. will need to spend \$600 billion per year for 50 years to build a smart grid with adequate buffering for the intermittencies of renewable energy. The cost to build a renewable energy system may come down as advances in robotics make terrestrial manufacturing less expensive, but on the other hand a 2013 study of energy storage found the specific materials needed to build a global-scale system will require approximately the entire global annual production of those materials for many

years [131]. For example, the study estimated it would take 28 years to mine enough lithium for batteries to support renewable energy at today's global power levels. If the world's power needs triple by 2100 as models suggest [132,133] then it should instead take 84 years of the world's mining to meet that need, but that fills the entire time. Since there are other economic needs for those same elements, the mining rate would need to effectively double for the rest of the century, increasing the cost of storage for renewables and making it even more likely the public will balk at the expense. The report finds that such (typically unaccounted for) costs will make a smart grid impractical unless energy storage life cycle can be increased by a factor of 5–10 [131]. Solving the energy problem with terrestrial renewables requires high levels of new spending, whereas bootstrapping SRSI can be done for far less completely within the existing space exploration budget, so it will be easier for policymakers to convince the public to make the investment. Furthermore, it is not an either/or choice. SRSI/SBSP can be developed in parallel with terrestrial systems for the best chance of success.

Penetration of renewable technologies into the global energy system may also be limited by environmental concerns at the energy collection sites [134], by available resources to manufacture the global system as mentioned above [135], and by the incremental cost versus the diminishing return of additional generators on the smart grid. Because of the intermittent nature of renewables, excess generation is required to get closer to full penetration, and the marginal addition of generation does not increase the power factor as much as the first generators on the grid; getting the next percent penetration is always more expensive than the previous percent [136]. Generators provide value at only 50%–80% of their original value by the time penetration reaches as little as 15% [137]. One 2012 study concluded, "Research as well as policy should take the possibility of a limited role for solar and wind power into account and should not disregard other greenhouse gas mitigation options too early" [137]. Another study examining the resource limitations (which drive the costs for renewables) concluded, "an overview of the land and materials needed for large scale implementation show that many of the estimations found in the literature are hardly compatible with the rest of human activities" [135]. At present, although renewable energy generation is growing, market forces have not allowed it to make even a dent in the use of fossil fuels since energy demands are growing faster than renewable energy [120,124]. Although penetration of renewables may reach no more than 10%–35%, a 2016 study finds even that much carbon reduction will have a societal value of US \$85–\$1230 billion (central value of \$400 billion) [138]. Bootstrapping SRSI will result in 100% penetration and thus will provide much more societal value than it costs, not even considering the many other benefits.

In view of these significant questions, the wisest approach is to pursue all of the potential solutions. Friedrich Wagner, who headed several fusion reactor experiments, considered the dire need to replace fossil fuels and the potential for success in developing (1) fusion, (2) inherently safe fission, and (3) adequate energy storage so renewables may become baseload power, and he wrote

Facing these perils energy research has to be tremendously intensified. Only the results of energy research may be the insurance that 9 billion people on Earth can live in peace. Facing the few options mankind has and the doubts on their potential, acceptability and sustainability, none of the three possibilities may be discarded or delayed [139].

Space development leading to SBSP gives us a fourth possibility to escape these perils, one that requires no new physics like fusion, costs less than renewables for higher penetration, and provides

EROI potentially much higher than any other. It should not be discarded or delayed, either. Among all the possible solutions, SBSP is uniquely positioned to overcome the economic barriers facing renewable energy because it can already be justified from existing space exploration budgets. It is also uniquely positioned to overcome the resource and environmental barriers facing renewable energy because it is located outside the limitations of this planet.

5.3.2. *Objection: why not put the self-replicating factories on earth?*

If solar energy has a low EROI when used on Earth, then how can a space-based solution have sufficient EROI when it is entirely driven by solar energy? It can for the same reason that a forest can collect solar energy and concentrate it as biomass. Energy that an autonomous system invests in itself through a net-positive metabolism, even if it is barely greater than 1:1 EROI, does not detract from human activity or lower our society's net EROI. This is why robotic autonomy is important for SRSI to be successful. However, if this autonomous leveraging gives solar a high EROI in space, then we might achieve the same solar EROI by bootstrapping robotic industry on Earth: a Self-sufficient Replicating Terrestrial Industry, or SRTI. After bootstrapping SRTI, it could build the renewable energy, storage and smart grid systems to concentrate energy so we can obtain it without much energy investment involving humans. Earth has many advantages over space that would make it easier and cheaper to start robotic industry, so what is the real advantage of going to space?

The answer to the objection is this: that we cannot scale up industry by a factor of a thousand – or even ten – here on the surface of Earth without causing great harm to the Earth's ecosystems. The primary benefit of space is real estate that biology does not need. Earth is the one special place in the solar system required by life, but machines can function anywhere else. We cannot scale up computing forever while it remains exclusively on Earth, and we cannot greatly increase mining of the necessary elements. Getting industry off the Earth's surface is the goal, not the means to the goal. All the global challenges we now face – population density, global warming, shortages of fresh water, cost of energy, running out of the cheapest ores so we must move on to mining the more expensive ones – are symptoms of a common problem: we are getting close to the limits of a planetary civilization.⁶ Because of that limit we cannot forever continue doing greater things as a species while relying on a single planet.

5.3.3. *Objection: space industry cannot help enough*

Another objection is that it is unreasonable to think we can put enough of our industry into space to make a difference. Lunar industry can make SBSP to beam energy to Earth as massless photons, but transporting manufactured goods that have mass is more problematic.⁷ The energy sector is a small fraction of the overall economy (there are more machines using energy than machines generating it), so how can it be worthwhile to move only the energy sector into space?

I have already argued that computing can eventually be put into space after SRSI has been bootstrapped, and this will relieve a potentially giant burden from Earth's environment. In addition, moving the energy sector, or a part of it, off-Earth is not a negligible

⁶ The ethical limit of a planet comes sooner than, and is more relevant than, the theoretical limit described by the Kardashev Level. Achieving a Kardashev Type 1 civilization without leaving the planet would require coating the entire globe with solar cells and thus driving most plants and animals to extinction.

⁷ It actually could deliver manufactured goods to the surface. SRSI could build a constant stream of one-way, landing spacecraft to bring down the manufactured goods. The landing spacecraft could be recycled for their metal and electronics for terrestrial use.

accomplishment. Projections say world population may exceed 11 billion by the end of the century and power demand could reach 51 TW (1610 EJ annually),⁸ four times the current demand [132,133]. That means there will be (roughly) four times as many machines on Earth using all that energy. The EROI of petroleum is about 20:1, meaning for every 1 unit of energy running machines to obtain petroleum we get back 20 units of energy to power all the machines [140]. That means (very roughly) 1/20th of the machines are working for the energy sector. As EROI declines both through exhaustion of petroleum and through adoption of lower EROI renewables, the fraction of machines supporting the energy sector should become much higher. Even if we can put no more than this portion of the machines on the Moon, that will reduce the burden on Earth's environment by a great amount.

However, space industry can do even better. Low cost, abundant energy will give us the ability to fund grand environmental projects. For example, over time, all of Earth's manufacturing could be moved underground where it will not compete with ecosystems on the surface. Robotic mining has already become advanced enough to do this. Then, terrestrial industry can be scaled-up with no environmental impact. Robots could also mine and recycle the landfills, remove carbon from the atmosphere, build greener cities, and restore habitats that were previously damaged. Two things we cannot put underground are (1) the renewable energy generators, and (2) the entire industry as it builds up to the level necessary to start going underground. Getting to that point would cause terrible damage to the Earth unless we use space-based power.⁹

5.4. Weighing probabilities

There is significant uncertainty whether renewable energy will be adopted quickly enough and with sufficient market penetration to avoid economic or environmental harm. There is also uncertainty whether it will provide adequate EROI for all nations to become highly developed and for civilization to be at its most vibrant. In my opinion SRSI/SBSP has the best chance of solving these problems because Stage 3 is not constrained by economics, global resources, or ecological impacts, and because the scaled-up robotic autonomy results in extremely high EROI. Even in Stage 2 it is buffered from economic stresses if the space program simply maintains current levels of funding for science and exploration. Thus, it uniquely decouples the world's energy and economy from the world's environment. Suppose SRSI and SBSP become available only after terrestrial renewables have scaled-up to maximum 35% penetration; then SBSP can still be a contributor by providing the other 65% to get us completely off fossil fuels. Suppose SBSP has a 50% chance of helping avert global economic and environmental disaster, and suppose the development of economic nuclear fusion also has a 50% chance. Since the two solutions are statistically independent, pursuing both simultaneously provides a 75% chance of averting disaster, reducing the odds of disaster by another 25% over just

fusion alone, and we get that extra chance for free by making space developing part of our space science within the existing budget. The seriousness of these potential humanitarian and ecological disasters makes this argument strong, because avoiding disaster is priceless, and even 25% of priceless is priceless.

Regarding the existential concerns, Matheny [141] assumed humanity could survive as long as *homo erectus*, so an extinction event has the expectation value of erasing 1.6 billion life-years from present and future humanity. He used asteroid impact statistics [142,143] to show that if half of these potential extinction events are preventable asteroid impacts, then a US \$20 billion space system to deflect asteroids has an expected cost of only US \$2.50 per human life-year, far less than we spend per life-year on insurance and healthcare, to state the obvious. Bootstrapping full SRSI may cost US \$9 billion per year for 40 years, so that is still only \$45.00 per life-year and the cost is already covered by our existing space budgets. The value is even greater when we consider that it preserves all the other species on Earth, provides other remedies for existential risks and lesser emergencies, and provides other benefits for the environment, economy, internet, computing, and space science. Matheny concludes, "We take extraordinary measures to protect some endangered species from extinction. It might be reasonable to take extraordinary measures to protect humanity from the same." However, this measure is not even extraordinary since we can obtain it for free by adopting more effective space science.

Our situation in this generation is unique because we live during the historic rise in human population that produced the first planet-scale challenges, and we are the first for whom SRSI capabilities have become achievable. Therefore, we are uniquely positioned as well as uniquely responsible to deal with this. Our biological conditioning may be the reason it is easy to ignore future people we will never meet and events that will probably not occur in our lifetimes. It therefore might help the unconvinced to think how future generations will be grateful to us if we choose to make them safe and prosperous by bootstrapping SRSI, and how we can enjoy today the knowledge that we are doing it.

6. Practical roadmap

Pragmatically (and unfortunately), Stage 1 seems to be a necessary stage to convince world leaders to embrace SRSI. If too much time is spent in Stage 1 convincing them, then it will delay the start of Stage 2 and the arrival of Stage 3, reducing the chances SRSI can provide help to the Earth quickly enough to avoid severe economic or environmental disaster. Therefore, we should adopt strategies to get through Stage 1 by convincing policymakers as quickly as possible.

6.1. Practical demonstration required

Some in the space settlement community believe the traditional, governmental leadership in space is underperforming, so they have pinned their hopes on newer, smaller commercial space companies to lead the way [144]. I disagree: while I believe commercial entities will make a substantial contribution, I do not believe they can do enough. When you examine a list of all the possible ways to make a profit in space, the activities fall short of completely bootstrapping SRSI. It may take some decades before "ignition" where the entire system pays back more than the ongoing investment. That is too long for individuals hoping to benefit from their investment, so they will invest elsewhere. This is why government must play the key role in leading its development, which brings us back to the original problem that government leaders must be convinced to invest in space settlement, something

⁸ The exact value does not matter for this discussion. A 2007 study [133] reviewed the 133 economic models in the literature that were subsequent to a 2000 climate report, and it found the 25th percentile prediction near 1100 EJ, the median near 1300 EJ, 75th percentile near 1800 EJ, and 95th percentile near 2550 EJ. Since global development is crucial to stabilizing the population, then failure to provide adequate clean energy to enable adequate economic development will exacerbate the problem. Arguably, engineering conservatism requires we minimize risk by planning to meet the energy levels in the higher end of the range plus a safety margin. 1610 EJ is only between the 50th and 75th percentiles and is therefore not too conservative, so it is not an exaggerated figure in this discussion.

⁹ Even industry on the Moon can be underground and powered by space-based power collectors to minimize impact to the lunar surface. The power collection would be in halo orbits at the first and possibly second Earth-Moon Lagrange points.

that has never happened before because it seems like a “nutty fantasy”.

Nothing beats a practical demonstration for convincing people that something is feasible. The strategy for convincing policy-makers (and the public they respond to) must involve smaller steps of implementing pieces of space industry, doing what we can as funding becomes available. The process of convincing leaders is therefore a process of actually starting space industry, but more slowly and piecemeal with inadequate funding, instead of bootstrapping it intentionally and as quickly as possible with adequate funding. This slower process delays the benefits of space industry, but as soon as the piecemeal progress has convinced enough of the public and their leaders that the overall program is achievable, and as the benefits become apparent, including its potential to solve world energy and climate problems, then I believe it is likely they will embrace Stage 2. This is especially true because Stage 2 already has enough funding if we simply direct the national space programs toward this purpose. The strategy to convince government leaders is therefore a matter of finding activities that:

- (1) can be justified within existing budgets and/or make a commercial profit,
- (2) contribute practically to the technology or infrastructure of space industry, and
- (3) demonstrate that space industry provides benefits.

There is an on-going discussion of strategies in the space development community about how we can convince government leaders to support space development. Some degree of consensus has emerged that the following steps are the most important:

- Space agencies will fund development of In Situ Resource Utilization (ISRU) technologies (e.g., water mining [25], oxygen extraction from regolith [28], and 3D printing landing pads from regolith [145,146]) to support their sortie and outpost missions. These technologies lower the mission costs and pay back the agencies in the near term. These technologies are a subset of what is needed for space industry, so developing them is also helpful for space development.
- The space agencies should eventually establish a propellant depot in space and give contracts to the space mining companies to extract water from asteroids and the Moon to make rocket propellant [147–151]. The propellant makes government space missions less expensive. These contracts give the mining companies cash flow, develop infrastructure in space that contributes to space industry, perfect the mining techniques, and prepare the mining companies for non-government customers.
- Space mining companies will begin selling propellant to space tug operators (or operating tugs themselves) to boost telecommunication satellites from Geosynchronous Transfer Orbit (GTO) or even from Low Earth Orbit (LEO) into Geostationary orbit (GEO) [147–149,151]. This will be a profitable revenue stream enabling space development companies to make further progress.
- The availability of cheap propellant will transform the goals of national space agencies, enabling them to do more frequent and more ambitious missions [152,153], which create a need for even more progress.
- These developments will make a lunar outpost more affordable [9] so eventually it will be established, provisioned by lunar mining [153–161]. Space agencies will fund the maturation of key technologies including the manufacture of solar cells [162,163] and structures [30,164–168] from in situ resources.

- Space tourism may establish facilities in space, and they will require provisioning with propellant and spare parts plus other services [169–171].
- If an organization successfully establishes a permanent settlement on Mars, it will become a customer for anything made in space¹⁰ [172]. Because of the Martian gravity, Mars will not become an exporter of manufactured goods for a long time and therefore will not directly contribute to in-space industry, but it will be a consumer of that industry, providing cash flow for the space development companies so they can make additional progress. Martian settlers will also develop mining and manufacturing technologies that have dual-use for the in-space supply chain.
- With these things happening in space, and with the robotics revolution continuing on Earth, it will become clearer to government leaders and the public that space industry is possible, highly desirable, and affordable. Then, government leaders will take on the mantle of the project and complete it for the good of humanity.

6.2. Building a cis-lunar water economy

Many space settlement advocates believe that mining water for propellant is the crucial element in a strategy to start space industry [147–151,173–176]. Therefore, it is of paramount importance in Stage 1 to ensure water mining becomes profitable. One of the challenges is funding the establishment of a propellant depot in cis-lunar space, possibly in LEO or GEO or at Earth-Moon Lagrange points. A depot will be needed to receive water from mining companies and distribute it to customers such as national space agencies and commercial space tug operators boosting communication satellites. The depot must include a water electrolysis capability, cryocooling and storage, adequate power generation and radiators for these capabilities, plus the usual spacecraft systems [147,177,178], so its cost will be significant. Capital recovery for the depot will be a significant contributor to the cost of propellant made in space. Technologies that make the cis-lunar water business more profitable include new propulsion that has both high thrust and high specific impulse instead of just one or the other. Higher thrust can boost a communication satellite to GEO more quickly, avoiding the loss of profits (upwards of US \$100 million) for a satellite owner during the months it takes a solar electric ion thruster to boost the satellite to GEO. The potential to eliminate that loss makes space-mined propellant more competitive. Higher thrust also allows an asteroid mining spacecraft to complete its round-trip mining mission more quickly, so it can acquire the water at less cost. High specific impulse decreases the amount of mined water that must be expended as propellant by the water-mining spacecraft, increasing the net yield, again lowering the cost. Other technologies that will make it more profitable include lower mass systems for propellant depots, faster or more efficient mining methods, and better methods to create space storable propellant like methane or isopropyl alcohol, which can be made with the carbon dioxide that is released by heated carbonaceous asteroid material or that is found in lunar ice.

An important way that space science can contribute to this process is by selecting missions that utilize space resources. For example, I have been working with Honeybee Robotics to develop CubeSats that mine water from an asteroid or the icy surface of a moon like Europa then use the water immediately for steam

¹⁰ Mars is too far from Earth to be the locus of bootstrapping a complete supply chain.

propulsion [179]. It can use the water to fly around in milligravity or hop on a body like Europa in higher gravity. The reason we proposed this project is because steam propulsion has dual-use; demonstrating it on science missions will help prove to investors the viability of the *cis-lunar* water economy. Our modeling shows that steam hopping works extremely well [180]. Prototypes of the small mining devices were built by my collaborators and they successfully extracted water from physically dry asteroid regolith simulants using realistic mineralogy for a petrological class 2 or 3 asteroid. The next step is to mature the steam propulsion technology through CubeSat test flights. ISS or sounding rockets can be used for tests of the mining apparatus in zero gravity. Finally, a flight version can be built for a mission to an asteroid or small moon, using mined water to never run out of propellant and to keep exploring. (There are ways to get the necessary delta-*v* to deliver a CubeSat to these targets.) Already in working this project we have conceived of new technologies for use in *cis-lunar* space.

A significant fraction of the space development community is working on technologies and business plans related to the *cis-lunar* water economy. NASA, with a view to buying propellant, is funding businesses and academia to develop the technologies [181–183]; they are also developing such technologies in-house [23,184–186]. NASA's annual Robotic Mining Competition [187] offers incentive points for robots that dig deeper into the regolith, simulating the process of acquiring lunar or Martian water from beneath a desiccated overburden, thereby crowdsourcing the development of digging techniques. At least three CubeSat lunar orbiter missions [188–190] and two lunar lander missions [185,191] are being funded or developed by national space agencies to prospect water on the Moon.

In all this effort, the science community (including the human spaceflight exploration community) is working synergistically with the space development community because their objectives overlap. Space agencies will benefit by having reduced cost for exploration missions so they can do more with the budgets they have. Science benefits because funding to characterize water resources leads to better understanding of solar system evolution. Commercial space companies benefit because the technologies they need are being developed. Ultimately, all humanity will benefit because a *cis-lunar* water economy makes it less expensive to set up a lunar outpost where robots can begin mining and manufacturing, leading to elements of a supply chain, making it more obvious for policymakers that the vast material resources of asteroids and the Moon can be used to solve economic and environmental problems on Earth.

7. Conclusion

I have argued that the bootstrapping of a Self-supporting, Replicating Space Industry is technologically feasible and that there is no reason to delay beginning. It will represent a transition in the form of our civilization, freeing us from the constraints of a single planet and giving us great benefits on Earth, both economic for humanity and environmental for all species, as well as making our existence in the universe more secure. It will also revolutionize science and exploration by providing material support and greater access to the space environment. The process of establishing this industry will take several decades. Spreading the costs over that period, humanity can easily fit it into our existing space science and exploration budgets if we have public support and visionary policymakers who make it a priority. However, the concept is abstract and just expensive enough that it may be difficult to convince them. The space community has been evolving strategies toward space development, and a number of themes are emerging, the most important of which is establishing a *cis-lunar* water economy by

mining asteroids and the Moon. Successfully doing that will lead to more activity in space, both scientific missions led by national space agencies and commercial activity. This will provide the opportunity to develop more technologies for space industry and to demonstrate some limited portions of an in-space supply chain. As these developments occur, and as robotics in terrestrial industry continues its revolutionary trajectory, eventually policymakers should embrace the vision to establish space industry. However, time is of the essence so that space industry may help avert the economic and environmental perils on Earth.

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Microwave processing of lunar soil for supporting longer-term surface exploration on the Moon



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ABSTRACT

The future of human space exploration will inevitably involve longer-term stays and possibly permanent settlement on the surfaces of other planetary bodies. It will, therefore, be advantageous or perhaps even necessary to utilise local resources for building an infrastructure for human habitation on the destination planetary body. In this context human lunar exploration is the next obvious step. Lunar soil is regarded as an ideal feedstock for lunar construction materials. However, significant gaps remain in our knowledge and understanding of certain chemical and physical properties of lunar soil, which need to be better understood in order to develop appropriate construction techniques and materials for lunar applications.

This article reviews our current understanding of the dielectric behaviour of lunar soil in the microwave spectrum, which is increasingly recognised as an important topic of research in the Space Architecture field. Although the coupling between the lunar soil and microwave energy is already recognised, considerable challenges must be overcome before microwave processing could be used as a main fabrication method for producing robust structures on the Moon. We also review the existing literature on the microwave processing of lunar soil and identify three key research areas where future efforts are needed to make significant advances in understanding the potential of microwave processing of lunar soil for construction purposes.

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1. Introduction

It is anticipated that future human exploration will involve longer-term stays and possibly permanent settlement on the Moon and planetary bodies such as Mars. To sustain such longer-term missions, it will be necessary to build robust infrastructure and habitats. Mass – a critical component of spaceflight – must be minimised in order to maximise cargo [1]. Because of the impracticality of transporting construction materials from the Earth, which would require huge mass for the anticipated scale of construction, using *in-situ* resources for construction on the target planetary bodies would be an ideal option. This research therefore addresses the field of construction processes which use lunar regolith and Additive Manufacturing techniques (a.k.a. 3D printing) on the Moon to build infrastructure and components such as human habitats, launching pads or scientific instruments.

In recent years considerable attention has been given to using

Additive Manufacturing techniques for extra-terrestrial constructions, because of the minimal waste of raw material, reduced human intervention and new architectural forms and functions [1]. It involves the process of constructing a 3D object by sequentially adding and bonding raw materials under automated computer control [2], using a specific binder which could be a chemical or a heat source. The potential raw material for construction on the Moon is lunar regolith. Regolith is the unconsolidated heterogeneous material overlying solid rocks [3,4]. For 3D printing using *in-situ* resources, the most effective way to bind the layers to fabricate a structure would be to either extrude a slurry of regolith or melted regolith, or sinter the raw material [1]. Sintering is a method where the material is heated to a temperature below its melting point to enable it to bond together to form a solid. The heat sources for fabrication on the Moon for either sintering or melting could be solar energy, nuclear energy or electromagnetic radiation, i.e. microwave radiation energy. Some 3D printing techniques including Fused Deposition Modelling and Selective Laser (or Solar or Microwave) Sintering could be used with these binding methods [1]. Among these, microwave processing (sintering or melting) is one of

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the most attractive fabrication methods for construction on the Moon because lunar regolith acts as a dielectric, readily absorbing microwave energy on the same principle as a kitchen microwave.

2. Microwave interaction with lunar soil

Microwave radiation is the region in the electromagnetic spectrum with a frequency range between 300 MHz and 300 GHz, and wavelength between 1 mm and 1 m.

Lunar soil is the finer fraction of lunar regolith, less than 1 cm in grain size [5]. The particle-size distribution of lunar soil is very broad and regarded as 'well-graded' in geotechnical terms. During the 4.5 billion year geological history of the Solar System, the lunar surface has been bombarded by micrometeorite impacts, solar flares and galactic cosmic radiation. Collectively, modification of the lunar surface material through these processes is termed 'space weathering'. The presence of single domain (40–330 Å in size) Fe particles in lunar soil (also commonly called nanophase Fe⁰ or np-Fe⁰) is thought to have been produced by space weathering processes. Previously, researchers [5–8] have hypothesised that the presence of this np-Fe⁰ in the lunar soil promotes coupling with microwave energy. Metals readily reflect microwaves, and the same metal in powdered form acts effectively as a conductor separated by dielectric (insulators such as particles and air) and absorbs microwave energy very effectively [5]. Microwave energy penetrates metals at a very shallow skin-depth, so metallic objects reflect microwaves. However, the minute size of np-Fe⁰ has an even smaller skin-depth allowing penetration of microwave energy. Lunar soil is a mixture of np-Fe⁰ grains separated by the dielectric glass and other rock-forming minerals (e.g., silicate, oxides, sulfides, etc.). The microwave absorbing abilities of the np-Fe⁰ particles thus create 'energy sinks' with the effective generation of large quantities of heat under microwave radiation [5].

Previous researchers have undertaken experiments involving heating of both actual lunar soil and lunar simulants at 2.45 GHz microwave frequency, the standard kitchen microwave frequency [5]. Because it is easily available and affordable, 2.45 GHz has been chosen for most lunar soil research experiments. Lunar soil and the lunar simulant JSC-1A appear to be completely melted at between 1100 °C and 1400 °C. JSC-1A, a reproduction of the original JSC-1 simulant, is crushed volcanic tuff with abundant glass with large amounts of nano-meter sized magnetite (Fe²⁺Fe³⁺O₄) grains [9]. Although JSC-1A mimics the geotechnical properties of lunar soil, it does not contain np-Fe⁰. As actual lunar soil availability is fairly restricted, the majority of studies have performed experiments on the lunar simulant JSC-1A, which is widely available from commercial sources [9,10]. However, using JSC-1A as a proxy for lunar soil with respect to microwave processing presents certain challenges. One such challenge includes the observation that JSC-1A when heated at 2.45 GHz did not absorb microwave radiation effectively up to 200 °C–400 °C, although it heated up rapidly at higher temperatures [11]. Thermal runaway condition is another challenge associated with microwave heating. Microwave energy is preferentially absorbed by the inner portions, leaving the surfaces less thoroughly heated. Microwave heating at 2.45 GHz is therefore usually discussed in combination with some other form of radiant heating [12]. Although microwave heating can be combined with other radiant heating, it is important to understand the factors contributing to the behaviour of JSC-1A when heated using microwave energy. Some of these factors are related to the fundamental physical properties of natural materials which affect and govern the nature of microwave coupling.

The absorption of microwave energy by a material depends on its dielectric properties. These properties help define three parameters: power density, heating rate and the half-power depth of

any material [5]. Thus, it is necessary to understand the dielectric properties of lunar soil and the factors which affect them. The following section briefly discusses some aspects of the dielectric properties and the work carried out by previous researchers to investigate the relation between these properties and some of the factors, e.g. density, frequency, temperature, etc.

3. Dielectrics

Dielectrics are essentially insulators. When exposed to an electromagnetic field, they become polarised [13]. The two important dielectric properties are dielectric constant and dielectric loss. Dielectric constant relates to the permittivity of a material. Permittivity is the ability of a material to store energy in an applied electromagnetic field and is the degree to which a material polarises in response to this applied field. The dielectric constant is sometimes also referred to as relative permittivity: the ratio of permittivity of the dielectric to the permittivity of a vacuum. Thus, the greater the polarisation developed by the dielectric in an applied electromagnetic field of given strength, the greater will be the dielectric constant [14]. An efficient dielectric supports a varying charge with minimal dissipation of heat. Dielectric loss is the form of loss in a dielectric which dissipates energy through the movement of charges in an alternating electromagnetic field as polarisation switches direction. This dielectric loss is utilised to heat the food in a kitchen microwave oven [14].

The two properties are crucial to determining the heating of a material in the presence of an electromagnetic wave such as the microwave. The properties depend on the frequency and are also influenced by density, mineral composition, grain size, moisture and temperature, etc. [15]. Study of the variation of dielectric properties with these factors will help determine the absorption spectrum for lunar soil in the microwave range. We have thus reviewed the data from previous studies to understand the relationship between dielectric properties and some of the factors mentioned above.

3.1. Dielectric properties of Apollo lunar soils

Olhoeft and Strangway [16] investigated the dielectric properties of the first 100 m below the Moon's surface by analysing nearly ninety-two Apollo lunar soil samples at frequencies ranging from 0.0001 GHz to 9 GHz. They used several core tube specimens of lunar regolith sampled from 1 to 3 m depth, to examine the dielectric properties of lunar soil as a function of density under controlled laboratory conditions [16,17]. A formula derived from studying these samples indicated that the density increases rapidly with increasing depth below about 1 m, but the density increase becomes unrealistic. Another set of data [18] for density versus depth profile is generated from the laboratory determined self-compression data of lunar soil samples. These data were used to derive estimates for the range of soil density using depth profiles in the lunar sub-surface at depths of up to 100 m. The data also show an increase in density with depth at the shallowest depths. However, these data are derived from the measurement of surface fines only and do not represent coarser rock mixtures or solid rock. The experiments conducted at the Apollo 17 site evidenced the presence of rock at close to 7 m depth. The authors claimed, therefore, that results from the estimates made for soils to the depth of 100 m are probably realistic only up to 7–10 m below the surface of the Moon [16].

According to their study, the dielectric constant in dry materials does not vary with frequency above a few KHz below temperatures of 200 °C [16]. However, it was found to increase with density, as shown in Fig. 1. It is worth noting that the samples, whether in solid

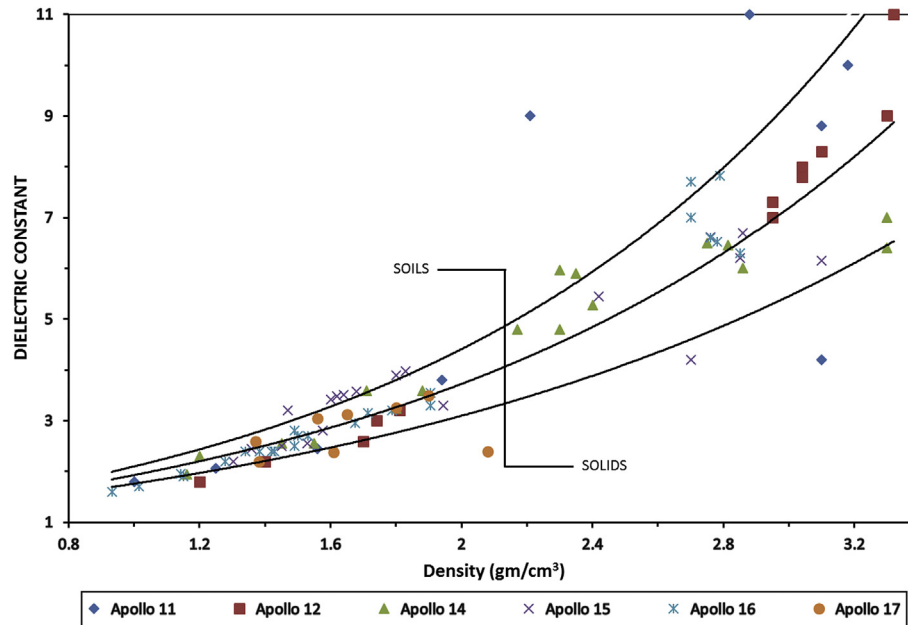


Fig. 1. Dielectric constant versus density (after [16]). Figs. 1–3 have been redrawn using the data reported in Table 2 of Olhoeft and Strangway [16]. In each case, the data have been fitted by standard regression analysis. The upper and lower bounds to the regressed data are also plotted at one standard deviation uncertainty.

or soil form, have the same density dependence.

Olhoeft [19] also observed that the dielectric constant is mainly dependent on density at higher frequencies.

As the lunar regolith varies considerably in composition, the literature offers relatively limited information about the variation of dielectric constant with the chemistry of lunar samples. However, Olhoeft and Strangway [16] studied the relationship between the ilmenite content (an iron and titanium oxide) and the dielectric constant. Fig. 2 shows that there is no correlation between the dielectric constant and the chemical index (total Fe and Ti oxides in this case) for either soils or solids. However, this lack of correlation

does not mean there is no relationship between the dielectric constant and the ilmenite content: increasing the ilmenite content increases the density. The result therefore implies indirectly that the ilmenite content has a correlation with the dielectric constant.

The factor indicating the material's ability to be polarised and heated is the loss tangent: a ratio of loss factor (dielectric loss) to the permittivity of the dielectric [20]. The loss factor measures the material's ability to transfer microwave energy into heat, and the permittivity measures its capacity to become polarised. The loss tangent is not easily measured as even very slight atmospheric moisture content in the Apollo samples would have a profound

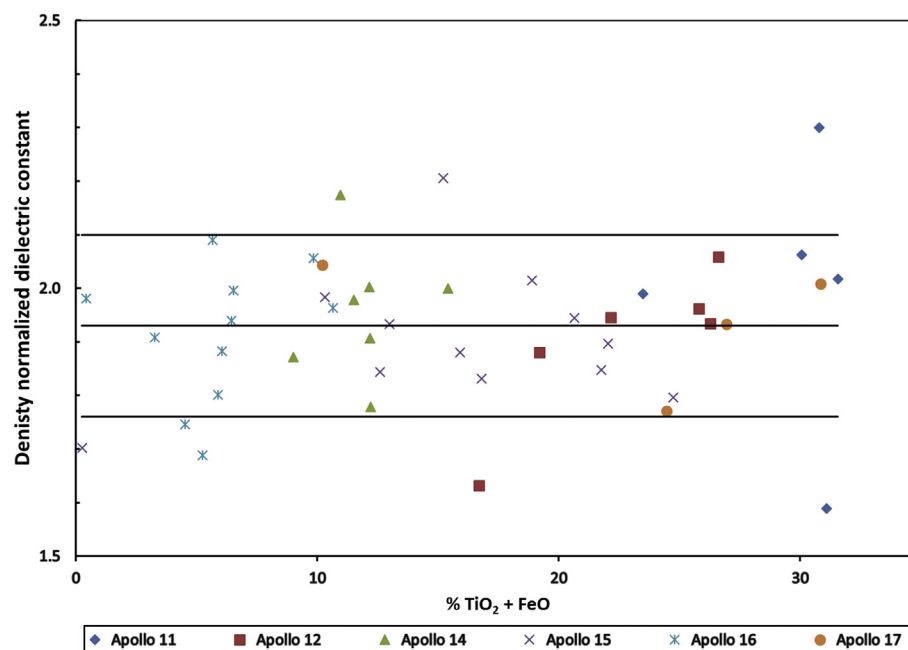


Fig. 2. Density normalised dielectric constant versus rock-forming oxides (titanium and total iron oxides) (after [16]).

effect. Some of the early Apollo mission samples were deemed to have been contaminated and yielded very high values for loss tangent because of the moisture effects. Thus, data from the samples collected by early Apollo missions were omitted while studying the dependence of loss tangent on density and ilmenite content. Data from the uncontaminated samples of later missions (Apollo 14, 15, 16 and 17) when studied showed a clear increase in the loss tangent with both the density and ilmenite content [16,21], as shown in Fig. 3.

Apart from density and ilmenite content, the loss tangent is thought to vary with frequencies above 0.0001 GHz. In summary, previous work has shown that there is a relationship between dielectric properties and three factors – density, frequency and ilmenite content in the frequency range of 0.0001 GHz and above [16].

3.2. Dielectric properties of lunar simulant JSC-1A

Calla and Rathore [15] reviewed the dielectric properties of the lunar stimulant JSC-1A. The measurements for dielectric constant and loss tangent were taken at four different frequencies: 1.7 GHz, 2.5 GHz, 6.6 GHz and 31.6 GHz. The rationale for choosing these frequencies was not given. However, the research was carried out for remote sensing applications, which may have dictated the choice of certain microwave frequencies. The dielectric properties were measured at temperatures ranging from -190°C to 200°C , mainly because this is the range of temperature experiences on the lunar surface between the lunar day and night cycles. Their work showed that the dielectric properties of JSC-1A increase with the increase in temperature at all four frequencies.

The same study found that at ambient room temperature (30°C) both the dielectric constant and the loss factor slightly decreased from 1.7 GHz to 2.5 GHz. From 2.5 to 6.6 GHz, the dielectric constant slightly decreased but the loss factor remained approximately the same, and further from 6.6 GHz to 31.6 GHz both properties again decreased. Though the decrease is small, it is an important indicator of the nature of dielectric properties with increasing microwave

frequency. The range of results obtained for the dielectric constant and loss factor at all four frequencies for JSC-1A at room temperature showed a good match with the value of some Apollo samples [15].

4. Summary and recommendations

Interest is growing in the planetary scientific community in exploring the possibility of using 3D printing techniques utilising microwave sintering of lunar regolith to construct human outposts on the Moon. Ondrej et al. [22] proposed an idea for a lunar base for a crew of ten with an accompanying astronomical telescope dedicated to observations in the infrared region of the spectrum at the Moon's North Pole. They also suggested that roads for transportation connecting major units of the settlement and the landing pads could be constructed using the sintering of the lunar regolith by emitted directed microwave radiation. It is also envisaged that the inflatable habitat structure could be covered with a minimum of 2 m of sintered regolith for protection against solar flares and micrometeorites. Various researchers' interest in this field is encouraging, exploring the utilisation of microwave energy in order to develop an extra-terrestrial construction process using 3D printing techniques on the Moon.

On the basis of the review presented above, three key research areas have been identified, which should be pursued in order to improve our understanding of the potential of microwave processing of lunar soil. These are:

- To address the challenges of heating lunar soil at 2.45 GHz and test heating at other frequencies of the microwave spectrum. Some other form of radiant heating such as the use of a microwave absorbing material (a susceptor) [12] can potentially be combined with the microwave heating to enhance the efficiency of the heating process. Such hybrid heating techniques could also reduce thermal imbalance in the material which can cause weak mechanical properties of the finished product. While addressing the challenges at 2.45 GHz, it is equally important to

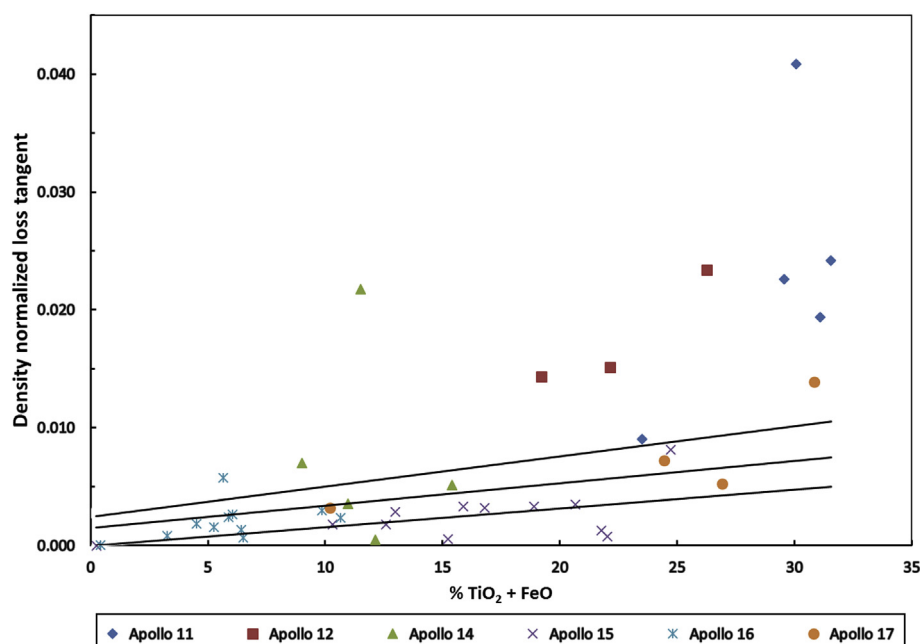


Fig. 3. Density normalised loss tangent versus titanium and total iron oxides content (after [16]).

examine the behaviour of lunar soil at other frequencies in the microwave range. Because the depth of penetration in a material will decrease with increasing frequency, a set of frequencies might be required for processing different depths of material, making investigating multiple frequencies an important research area.

- To understand the behaviour of dielectric properties of lunar soil with certain factors such as density and particle grain size. Understanding the dielectric properties of lunar soil is important to evaluate the coupling behaviour of microwave with it. Their variation with these factors will contribute in determining the absorption spectrum for lunar soil in the microwave range. The dielectric properties would help engineers in calculating the response of the lunar soil to microwave heating for construction purposes. Meantime scientists' knowledge of these properties can help design active and passive sensors for remote sensing studies of the Moon [15].
- To test the strength and endurance of the product fabricated by microwave processing of lunar soil for micrometeoroids and radiation damage.

It is mandatory to ensure that structures built on the Moon can withstand the micrometeorite impact and radiation damage protection for long-term functional operations in the lunar environment. Understanding the mechanical properties of the fabricated structures by microwave processing of the lunar soil is therefore crucial.

The value addition to this research will be the opportunity to experiment with Apollo lunar samples and analyse the effect of microwave heating on them, bearing in mind that the Apollo landings were restricted to near the equatorial regions on the Moon, the samples collected representing only limited geographical extent. The lunar geology, however, varies at different locations, so sample return missions are required from a range of lunar locations. It would also be advisable in the future to conduct *in-situ* measurements on lunar robotic missions, to test the samples for *in-situ* resource utilisation experiments involving microwave processing.

Detailed research in the key research areas mentioned above, involving microwave processing of lunar soil, will benefit both the scientific and engineering communities to better understand and explore our nearest neighbour – the Moon.

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Scientific return of a lunar elevator



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ABSTRACT

The concept of a space elevator dates back to Tsilokovsky, but they are not commonly considered in near-term plans for space exploration, perhaps because a terrestrial elevator would not be possible without considerable improvements in tether material. A Lunar Space Elevator (LSE), however, can be built with current technology using commercially available tether polymers. This paper considers missions leading to infrastructure capable of shortening the time, lowering the cost and enhancing the capabilities of robotic and human explorers. These missions use planetary scale tethers, strings many thousands of kilometers long stabilized either by rotation or by gravitational gradients. These systems promise major reduction in transport costs versus chemical rockets, in a rapid timeframe, for a modest investment. Science will thus benefit as well as commercial activities.

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1. Introduction

The long term exploration and development of space would greatly benefit from the use of planetary-scale tethers, both as dynamic tools and for space elevators [1–3].

Free-flying tethers must rotate to stay in tension. Those that rotate so as to cancel the relative motion between the tip and a planetary or satellite surface are called rotovators [4]; such tethers may be used to set up transportation systems moving material to and from planetary surfaces at low relative velocities and without the expenditure of fuel [1,5]. A space elevator is a tether deployed as a static or orbiting structure stretching from a celestial body out into space [2]. In order for a space elevator to remain static (stationary with respect to the surface of the body it is attached to) its center of mass must be in a stationary orbit, with the force of gravity on the tether being balanced by either the centrifugal force of rotation (for a terrestrial elevator) [6] or tidal forces (for a lunar elevator) [7] on the mass of the tether plus any counterweight above the center of mass.

The proposed Deep Space Tether Pathfinder (DSTP) mission is intended to both test the technology of the prototype LSE and provide a substantial scientific return by doing touch-and-go sampling of a selected area on the lunar surface. The rotation of the DSTP would be used to match the relative velocity between its

lower tip and the Moon during a flyby, allowing for the collection of surface samples from a suitable scientific target, in the default mission from the floor of Shackleton Crater in the lunar South polar region. The collected material would then be returned to Earth by the release of a return capsule roughly one half rotation period later, when elevator tip velocity is appropriate for a direct return trajectory. After sample release, the DSTP would continue into deep space, allowing for long term observations of the performance and micrometeorite resistance of the tether in the space environment and the first test of kilometeric radio interferometry in deep space.

The proposed LSE Infrastructure (LSEI), the first true space elevator on any celestial body, is planned as a follow-on to the DSTP. The LSEI would be a very long tether extending from the lunar Surface, through the Earth-Moon Lagrange L1 point (EML-1) 56,000 km above the Moon, and on into cis-lunar space. The LSEI prototype, scaled to be deployable with one launch of a heavy lift vehicle, would be able to lift roughly 5 tons of lunar samples per year, and deploy a similar quantity of equipment onto the lunar surface. The LSEI would enhance a crewed Deep Space Habitat (DSH) at EML-1, for a small fraction of the total DSH cost by, for example, supporting tele-robotic exploration on the surface. Similar scientific work could be accomplished by a farside LSE, which could also provide real time communications to the farside, opening an entire lunar hemisphere to exploration.

Of the possible near-term space elevator deployments (Earth, Moon, Mars), a lunar nearside elevator is undoubtedly the most technically feasible. Modern high strength polymers such as Ultra-high-molecular-weight polyethylene (UHMWPE) (brand name

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Dyneema[®]) [8] and poly-phenylenebenzobisoxazole (PBO) (brand name Zylon[®]) [9] are inexpensive and available in large quantities, ample for LSE tethers. Even a prototype LSE, deployed by a single launch of an existing launch vehicle, would serve as the linchpin in a lunar delivery service, the LSEI, capable of transporting up to 5 tonnes of material to and from the lunar surface per year and supporting a wide variety of scientific research, including on and near the lunar surface, at the L1 Lagrange point, and deep into cislunar space at the counterweight.

The ΔV required for a rocket to ascend from lunar surface to EML-1 is 2.7 km s^{-1} . Goff [10] showed that the typical payload mass fraction for such a rocket is 34%, $\sim 1/3$. A rocket which puts the 49 tonnes LSE at EML-1 would otherwise be capable of depositing 16 tonnes on to the lunar surface. So for LSE payload of 0.1 tonnes, this is equivalent to $16/0.1 = 160$ payload landing cycles, which is the number of cycles to recoup the LSE launch cost. For sample return, another factor of three applies, so ~ 53 sample return cycles would recoup the launch cost.

While the initial LSEI would not be able to deliver human passengers to and from the lunar surface, a functioning LSEI prototype would enhance the capabilities of humans in a Deep Space Habitat (DSH) in a Lissajous orbit around EML-1, as envisioned in the 2011 Global Exploration Roadmap [11,12]. The LSEI would: enable astronauts to deliver rovers and instruments to the lunar surface, teleoperate that equipment from only 56,000 km altitude, lift selected surface samples to EML-1, evaluate those samples, and use that evaluation to direct the acquisition of further samples.

2. The scientific goals of the Deep Space Tether Pathfinder

The DSTP would be spacecraft with a 5000 km long tether, with a tether mass of 2228 kg and a total system mass of 3043 kg, rotating every 2.44 h with a sampling probe on the far tip [13]. The DSTP would flyby the Moon as a rotovator [4] to collect lunar samples in a touch-and-go manner, followed by a cruise in deep space as an engineering test of the tether technology needed for the first LSE [13]. The DSTP would be the first tether actually deployed as a rotovator, rotating to match the velocity of its sampling tip with the lunar surface, which would enable sample acquisition from a scientifically interesting region, such as the permanently shadowed regions at the lunar poles. Approximately 2 h after sample collection the DSTP would use its rotational velocity to sling-shot the sample back to Earth for a ballistic reentry with a minimal expenditure of fuel. The DSTP would then continue on into deep space for a long-duration exposure test of the radiation and micrometeorite resistance of the tether's design, and also a test of kilometric radio interferometry in deep space [13].

The primary scientific justification of the DSTP mission would be lunar sample return; its lunar science objectives address every one of goals in the "Lunar Polar Volatiles and Associated Processes" white paper submitted to the 2011 Decadal Survey [14]. Current DSTP mission planning has focused on sampling volatiles on the shadowed floor of Shackleton Crater at the lunar South Pole, which is a cold-trap and should collect substantial amounts of surface volatiles from collisions and out-gassing on other areas of the Moon [15]. Near-surface imagery returned during the sample collection process will help to assess the nature and distribution of volatiles, even if sample return is not successful. (Portions of the Shackleton Crater rim are in sunlight at any time of month [16], providing illumination of the crater bottom that is typically several times full-Moon illumination on Earth.) The search for lunar volatiles ranks high in the decadal surveys of planetary science [14], and the Permanently Shadowed Regions (PSRs) on the Moon are arguably the easiest such locations to access in the solar system. The PSRs contain an important scientific record of the history of volatiles in

the inner Solar System, and a potential resource for future economic development [17,18]. These regions have been the target of intense scientific interest in the last decade, and were the target of the LCROSS impactor [19], but surface sampling by landers or rovers is complicated by the lack of solar power and direct communications with Earth in a PSR.

Fig. 1 shows the general DSTP trajectory near the Moon in a 2-body gravitational simulation, while Figs. 2 and 3 show the DSTP tether positions 1 h before and just after the time of sampling, respectively. Fig. 4, an enlargement of Fig. 3 (inverted so that the crater floor is at the bottom), shows that the tether descends almost vertically at the lunar surface; to a surface observer the motion of the probe up and down inside the crater would appear to be almost completely vertical, enabling sampling from topographically rough regions. In addition, there is a clear line-of-sight back to the main spacecraft at the other end of the tether, allowing for direct relay communication with Earth at the time of sampling.

Shackleton Crater sits on the boundary of the older and much larger South Pole-Aitken Basin, a ~ 2500 -km diameter impact basin which brought up material from deep inside the lunar interior. Given the surface albedo results from Selene [16], it is highly likely that a sample collection from the floor of Shackleton Crater would include rock or regolith samples from the South Pole-Aitken Basin [21].

A proposed South Pole-Aitken Basin Sample-Return (SPA-SR) mission was highly ranked by the National Research Council Planetary Science Decadal Survey [14] and was suggested for a New Frontiers class mission, with a cost cap of \$1.0 billion. The DSTP would provide a first look at both South Pole-Aitken Basin material, and at the volatiles in a PSR, within a NASA Discovery mission cost cap.

Another scientific goal of the DSTP is to deploy the first radio interferometer for the kilometric spectral region between 10 kHz and 1 MHz, which is largely unexplored for radio astronomy as these wavelengths do not penetrate the Earth's ionosphere. The proposed radio interferometer, the Dark Ages Pathfinder (DAP), would consist of two 10-km dipoles attached to either tip of the DSTP, providing an interferometric baseline of ~ 5000 km and allowing for rotational synthesis as the tether rotates. At 1 MHz this baseline would allow for an angular resolution of approximately 1° , allowing detection of candidate point sources and limited mapping of extended sources. The DAP would complement the proposed Dark Ages Radio Explorer (DARE) [22], which is to operate over a higher frequency radio bandpass of 40–120 MHz. The DAP's ability to distinguish solar system, galactic and cosmological sources from

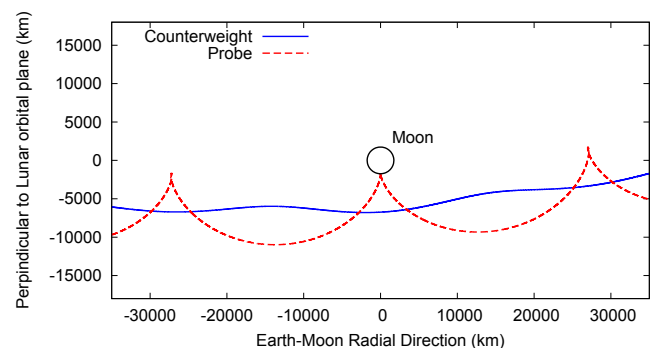


Fig. 1. Trajectories of the two tips of the DSTP during the entire lunar sample return period, as seen from a selenocentric reference frame [13]. The main spacecraft, assumed to include the upper stage as a counterweight, is considerably more massive than the probe and is thus closer to the tether center-of-mass, which executes a smooth ballistic motion. This Figure represents 6 h of total motion.

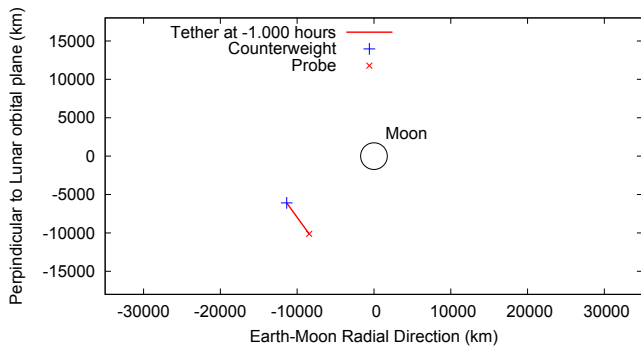


Fig. 2. The DSTP 1 h before the touch-and-go sampling, from the simulation shown in Fig. 1.

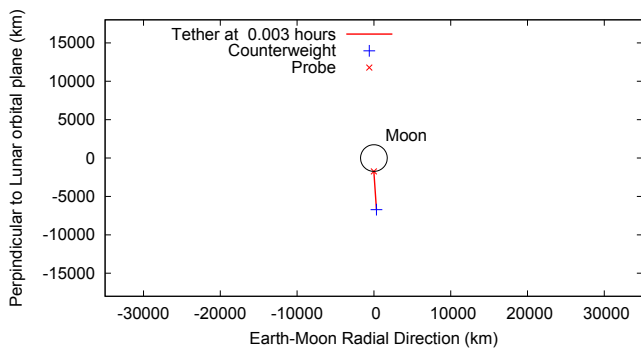


Fig. 3. The DSTP 10 s after the time of the touch-and-go sampling, from the simulation shown in Fig. 1.

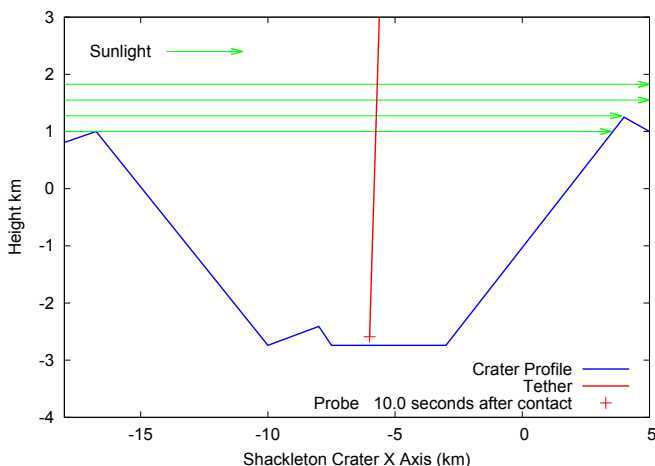


Fig. 4. A cross sectional view of Shackleton Crater from Lidar data [20], with the DSTP tether and probe 10 s after closest approach, when it is ~ 100 m above the crater floor [13]. This image is from the same simulation sampled at the same time as for Fig. 3. The green horizontal arrows indicate the maximum illumination of the crater by the Sun; the crater interior below these lines is permanently shadowed (the sampling probe is in shadow for ~ 2 min). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

terrestrial interference will improve as the distance from the Earth increases. Observations with Radio Astronomy Explorer B [23] indicate that at the lunar distance the Earth interference is typically about 2 orders of magnitude above the celestial background. The terrestrial interference should thus decline to a manageable level when the DSTP is ≥ 3 million km from Earth, or ~ 2 weeks into

the extended deep space mission.

3. The prototype Lunar Space Elevator infrastructure

The LSEI currently is planned to be executed in a single Discovery class mission, starting with the delivery of 41,750 kg of Zylon HM fiber plus 6,950 kg of associated equipment to the EML-1 Lagrange site. Fig. 5 shows to scale the major components of LSEI, the string, the Landing Platform (LP), the supply depot at EML-1, and the CounterWeight (CW), while Table 1 provides basic information about the default LSEI for both lunar hemispheres.

The LP attached to the tether descends to the lunar surface in the initial prototype deployment. After landing, we refer to it as the Landing Station (LS); the planned LS location is Sinus Medii, near 0° Latitude and Longitude on the lunar nearside. Fig. 6 shows the topography of Sinus Medii from the Surveyor 6 lander [24]. There are 3 natural locations for long-term scientific observations from the LSEI, the LS on the surface, the deployment platform at EML-1, and the Counterweight (CW) at the far end of the elevator. All 3 locations should be instrumented, both for the scientific return and to monitor the elevator's performance.

The primary initial science goal of the LSEI prototype mission is the return of the lunar samples to Earth. LSEI will take a core sample upon landing and will deliver one or more microrovers to the lunar surface to assist in collecting surface samples. LSEI will return up to 100 kg of samples in the first Lift from the lunar surface, using a reusable solar-powered lifter. Sample returns can be done without fuel using a nearside LSE, as material (in a suitable return capsule) could be simply released at the right moment for a direct reentry trajectory to a desired landing location; anything separated from the LSE an altitude $\geq 220,670$ km above lunar surface will re-enter the Earth's atmosphere in ~ 1.4 days at a velocity of ~ 10.9 km s⁻¹ without any expenditure of fuel. This same technique can be used to return high value ore samples or mining products from a lunar mining enterprise.

There are some important sites with materials of economic interest near to the EML-1 LS. The nearby crater Lalande is known to have some of the highest concentrations of surface KREEP deposits on the Moon [26], as well as 19 impact melt pits, possible sites for volatiles [27]. Also, nearby mare areas appear to have elevated concentrations of Helium-3 [28]. Regardless of landing site, lowland regolith contains concentrations of lunar volatiles which can be used for propulsion and life support. The LS will also become an

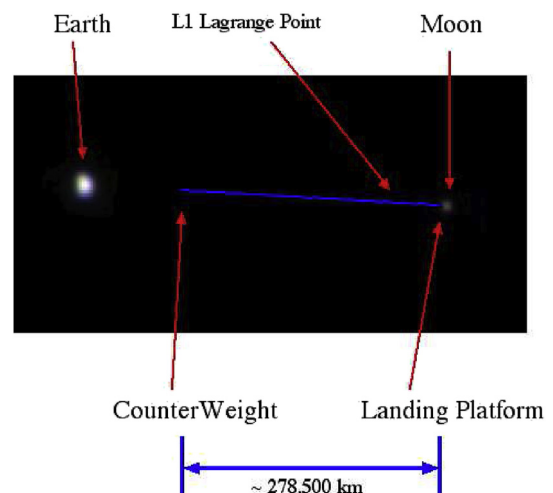


Fig. 5. The components of the LSEI LSE, to scale, superimposed on an image of the Earth-Moon system from the Juno spacecraft.

Table 1
Prototype Lunar Elevators [25].

Parameter	Elevator location	
	Nearside	Farside
Tether Material	Zylon PBO	Zylon PBO
Length	278,544 km	297,308 km
Total LSE System Mass	48,700 kg	48,700 kg
Surface Lift Capacity	128 kg	110 kg
Total Taper (max/min area)	2.49	2.49
Maximum Force	517 N	446 N
Landing Site	0° E 0° N	180° E 0° N

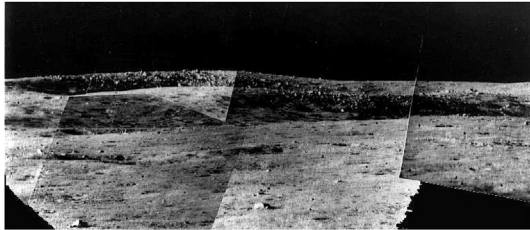


Fig. 6. Sinus Medii from Surveyor 6, taken about 44 km from the proposed landing site (Figures. 7–41 from Ref. [24]).

important transit point for long distance lunar rovers which will recover samples over large distances much more cheaply than using rocket landers.

LSEI plans to use Single Cube Retroreflectors (SCR) as Laser ranging targets [29] for navigation during deployment of the LSE and the Landing Platform. The SCR would become a permanent addition to the Lunar Laser Ranging (LLR) retroreflector network. The LSEI would thus augment LLR studies of basic physics, lunar dynamics, and Earth-Moon celestial mechanics [30].

Poorly understood electrostatic levitation and transport of dust happens in regions near the lunar terminator [31], and may be important in the covering of PSR volatiles over geologic time. If electrostatically-levitated dust is present LSEI will sample it *in situ* with passive Aerogel collectors or electrets (permanently charged materials), deployed at altitude during periods when an elevator lift is not scheduled.

The CW can observe the Earth from over 100,000 km away, outside of the existing satellite constellations. It will be able to observe the magnetic and charged particle environment in the Earth's magnetopause as the CW goes in and out of the Earth's magnetosphere twice per lunar month.

In addition, EML-1 is a logical location for the observation of the nearside of the Moon. One fairly small optical telescope (~20 cm aperture) could continuously observe the entire nearside, searching for meteorite impacts and transient lunar phenomena, and also be able to detect and characterize the orbits of close lunar orbiters.

Various factors could limit the useful life of an LSE, with micrometeoroid impacts being an especially serious threat to tether longevity (in cislunar space there is no significant flux of man-made orbital debris). The LSEI would be a very thin tether, with a radius of ~ 0.2 mm if it were just a single strand. Such a strand would be broken if impacted by a meteorite with a mass as small as 10^{-5} gm. A variety of methods have been used to determine the micrometeorite flux in near-Earth and near-lunar space [31,32]; the cumulative flux of meteorites of this mass and larger is $\sim 10^{-8} \text{ m}^{-2} \text{ s}^{-1}$. The LSEI is sufficiently long that its surface area would be $\sim 10^5 \text{ m}^2$; if the LSEI were made from a single strand it would have a micrometeorite impact lifetime measured in hours. The LSEI will have to deploy a multiline fail-safe system such as the “Hoytether” [33] to

achieve a design life-time of 5 years; testing of the chosen micrometeorite protection system in deep space would be one of the primary engineering goals of the DSTP mission.

4. A farside Lunar Space Elevator

An elevator on the lunar farside (with a landing point at or near longitude 180°, latitude 0°) could fulfill many of the scientific and logistical goals of a nearside LSEI, but would also provide unique advantages of its own [25,34].

4.1. Sample return from the lunar farside

To date, all lunar sample returns have been from 9 sites on the lunar nearside [35]. The LSE in Table 1 assume natural elevator landing sites (i.e., directly beneath the Lagrange Point), as these seem most appropriate for an initial elevator deployment. An EML-2 LSE would thus provide an immediate sample return from a previously unsampled region (and, indeed, from a previously unsampled hemisphere). The EML-2 landing site (Fig. 7) is near Lipskiy Crater and just North of Daedalus Crater in very rugged and heavily cratered terrain in the lunar highlands.

4.2. Farside radio astronomy

The farside of the Moon is totally shielded from terrestrial radio transmissions, and is arguably the best place in the solar system for a radio astronomy base. The Earth is a major source of radio noise and interference, both natural and artificial, and its ionosphere blocks ground based observations at frequencies ≤ 10 MHz. The farside LSE LS at 180° E longitude point would be an ideal location for such a farside radio astronomy base, far from terrestrial interference and with a view of the entire sky. Many have proposed radiotelescopes there, e.g. Jester and Falcke [36]; an EML-2 LSEI would considerably reduce the cost of building and supplying a lunar farside radio telescope system, enabling both the installation of antennas on the surface at the LS, as well as vertically using the lower portion of the elevator as an antenna tower [34]. Decametric and kilometric radio astronomy could be conducted during the

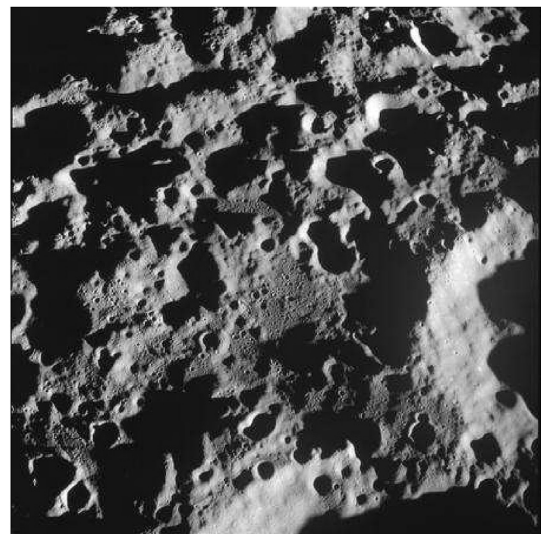


Fig. 7. Apollo Image AS11-44-6607, taken by astronaut Michael Collins during the Apollo 11 mission, July, 1969, from an altitude of ~ 110 km. This image shows the very rough highland terrain at the farside elevator LS (the default LS is towards the upper left of this image). This part of the lunar terrain has never been explored or sampled by any surface mission.

lunar night, when radio interference from the Sun is also blocked and when solar powered climbers would not be using the near surface part of the LSE.

The farside is recommended as a radio quiet zone by the International Telecommunications Union under ITU-R RA.479. Maccone [37] has proposed a Protected Antipode Circle [PAC], a more extensive protection zone than that proposed by the ITU. The PAC centered around the antipode on the farside spanning an angle of 30° in longitude and latitude in all radial directions from the antipode. The PAC is the most shielded area of the farside, with an expected attenuation of man-made RFI of 100 dB or higher. Neither the PAC nor ITU farside rules have been adopted by any law making body; in any case a farside LSE would have to avoid interference with farside radio observatories, whether at the LS or installed elsewhere by other missions.

4.3. Other farside science

An EML-2 LSE would enable a variety of other farside science, including the monitoring of particles and fields in near interplanetary space at EML-2 and at the far end of the elevator, which would enable deep monitoring along the Earth magnetotail at Full Moon. From an EML-2 station almost the entire farside could be monitored for meteor impacts, complementing the terrestrial monitoring of the nearside for impacts [38]. The monitoring of the time and location of farside impacts will be especially important if a nearside lunar seismological network is re-established, as impacts on the farside will provide seismic waves traversing the lunar core to nearside seismometers. An EML-2 LSE would extend the lunar seismological network to the farside itself, providing a truly global lunar monitoring network. Even one seismometer at the farside LS would enable the seismic study of the entire lunar interior [39] in combination with the locations and times of nearside impacts provided by the ongoing terrestrial monitoring of meteorite impacts of the visible lunar surface [38].

4.4. Farside communications relay

Communications has always been a severe complication for the engineering of missions to the lunar farside, as there is no direct line-of-sight between the Earth and any location deep in the farside (librations bring occasional line-of-sight to locations at the farside-nearside boundary). An EML-2 LSE would provide a communications mast visible from almost any location on the lunar farside, and could thus serve as a relay for communications with the Earth. A farside LSE communications relay would literally open an entire lunar hemisphere for further exploration.

5. Facilitation of mars exploration

Ishimatsu et al. [40] have shown that the launch weight of missions to Mars can be reduced by 68% by using oxygen derived from the Moon as propellant. A LSE would allow relatively inexpensive transport of lunar regolith to a cislunar oxygen production facility, further reducing transportation costs. Volatiles derived from the lunar regolith could fulfill most of the life support consumables required by a crewed Mars mission. Resources from the Moon can facilitate missions to anywhere in the solar system [17], and lunar elevators could greatly reduce the cost of transporting such materials into space.

In addition, the velocity of the counterweight of a farside LSE would provide significant ΔV for injection into a trans-Mars orbit. Material lifted past EML-2 could be sent to Mars with a minimal investment in fuel, helping to support long-term colonies on that planet.

6. Conclusions

The DSTP and the LSEI are crucial first steps in the development of space elevators, and in future tether missions, but can and must be justified on the basis of returned science, in addition to their engineering return. Building the DSTP is feasible, has an exciting scientific return and would be a natural first step in developing an elevator-based lunar infrastructure program, leading to the construction of the LSEI and in due course the development of a true transportation infrastructure for the inner solar system.

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A cislunar transportation system fueled by lunar resources



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ABSTRACT

A transportation system for a self sustaining economy in cislunar space is discussed. The system is based on liquid oxygen (LO₂), liquid hydrogen (LH₂) propulsion whose fuels are derived from ice mined at the polar regions of the Moon. The elements of the transportation system consist of the Advanced Cryogenic Evolved Stage (ACES) and the XEUS lander, both being developed by United Launch Alliance (ULA). The main propulsion elements and structures are common between ACES and XEUS. Both stages are fully reusable with refueling of their LO₂/LH₂ propellants. Utilization of lunar sourced propellants has the potential to dramatically lower the cost of transportation within the cislunar environs. These lower costs dramatically lower the barriers to entry of a number of promising cislunar based activities including space solar power. One early application of the architecture is providing lunar sourced propellant to refuel ACES for traditional spacecraft deployment missions. The business case for this application provides an economic framework for a potential lunar water mining operation.

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1. Introduction

The key to the success of the human venture in space is the establishment of a self sustaining space economy. In this economy, space activities generate wealth, not consume wealth. In the self sustaining space economy, the free market drives innovation, spurring growth and competition which drives more innovation. However, to date, there have been only two business models in space that work. The first is sell goods and services to a government. A government, in turn, has a number of potential purposes for space activity including national security, science and national prestige. However, this business has great difficulty harnessing the power of the free market. The second is providing commercial communications services to terrestrial customers. This involves building, deploying and operating communications relay satellites in Earth orbit. According to the Space Foundation's Space Report [1], the total value of all space goods and services in 2014 was approximately \$300B. However, only a small fraction was attributed to building and launching satellites. The single greatest contributor was terrestrial applications of the Global Positioning System (GPS).

To create a self sustaining space economy, commercial economic activities in space must be developed. Non-governmental wealth creating economic activities require consumers, and it happens that

all consumers currently reside on Earth. Hence the challenge is to develop space activities that deliver benefits worth paying for to people on Earth. The enormous distances between objects in space suggests that the first place to look for activities that benefit Earth is in the vicinity of Earth and our nearest neighbor, the Moon. In other words, any near term self sustaining economic activity will likely take place within cislunar space. One might also include near Earth asteroids in the mix. John Marburger, the Science Advisor for President Bush, in a 2006 address at the Goddard Symposium [2], summarized it quite nicely: "It is likely that these near-Earth applications will always dominate the use of space because Earth is where the people are, as well as the environment that sustains them." (I was in the audience for Marburger's speech and it has shaped my thinking ever since.)

2. The cislunar econosphere

The first step in building a self sustaining economy in cislunar space is understanding what activities are possible and where they might occur. Fig. 1 shows the basic geography of cislunar space and a list of possible economic activities. There are four main regions of cislunar space that are suitable for economic activities of various kinds: low Earth orbit (LEO), geosynchronous orbit (GEO), high Earth orbits, and the lunar surface. For simplicity, I have omitted a class of useful orbit between LEO and GEO. These mid-Earth orbits (MEO) are primarily useful for navigation satellites like GPS.

LEO consists of a region of space up to about 1000 km above the

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Nomenclature

ACES	Advanced Cryogenic Evolved Stage
CRYOTE	Cryogenic Orbital Test
DLRO	Distant Lunar Retrograde Orbit
EML1	Earth Moon Lagrange Point 1
EML2	Earth Moon Lagrange Point 2
GEO	Geosynchronous Earth Orbit
GPS	Global Positioning System
ISS	International Space Station
IVF	Integrated Vehicle Fluids
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
NRO	Near Rectilinear Orbit
ULA	United Launch Alliance
XEUS	eXperimental Enhanced Upper Stage

Earth's surface. Useful orbits in LEO are nearly circular and have orbital periods of around 90 min. A wide range of inclinations are employed. Highly inclined orbits are useful for Earth observation and sensing. Low inclined orbits are easily accessed and are suitable for way points to locations beyond LEO and space stations like the International Space Station (ISS).

GEO orbits are useful for communication and Earth observation. These orbits have a period of approximately 24 h. Hence, satellites in geosynchronous orbit appear fixed (or nearly fixed) with respect to the surface of the Earth. True geostationary orbits have zero inclination, but in practice, some small inclinations are employed. GEO is also expected to be the preferred orbit for space based solar power satellites [3].

High Earth orbit is a collection of orbits that are useful as way-points or staging points to the lunar surface or locations beyond cislunar space. They consist of halo orbits circling one of either

Earth-Moon Lagrange point 1 or 2 (EML1 or EML2), or a class of orbits called distant lunar retrograde orbits (DLROs) or near rectilinear orbits (NROs). All of these orbits are similar in the energy needed to reach them from Earth and have different features that make them useful for different purposes. For the remainder of the paper, I will use EML1 as a proxy for this class of orbits.

The lunar surface is the key location for resource extraction [4,5]. As Marburger said a decade ago, one of the goals of the space program is to bring the resources of space within the economic sphere of humankind. The Moon is the obvious place to start. The lunar poles are likely to be an early location for this kind of activity for two reasons. First, due to the fact that the Moon's rotation axis is very nearly perpendicular to the ecliptic, there are region near the poles that are Sunlit for nearly 100% of the time. For the same reason, there are regions near the poles that are in permanent shadow. Nearly permanent sunlight provides nearly unlimited solar power for resource extraction activities and avoids the 14-day night of equatorial regions. Second, the permanently shadowed regions contain, we now know, large quantities of water ice, as much as 10 billion tons per pole by some estimates [6].

Water extracted from ice is a critical resource for the cislunar economy. It is obviously required to support any human activity and is easily separated into its constituent oxygen and hydrogen through electrolysis. Oxygen is essential for breathable air. When liquefied, hydrogen and oxygen form the most powerful chemical rocket propellants known. Mining lunar ice for rocket propellant is likely to be the first economic use of lunar resources.

3. Transportation within cislunar space

Current activities in space are limited in large part by transportation costs. It costs \$5000 to \$10,000 per kilogram to get from Earth to low Earth orbit. It costs four times as much to get to GEO and seven times as much to get to the lunar surface. The key to enabling a self sustaining cislunar economy is to dramatically reduce the cost of transportation. And the key to lowering

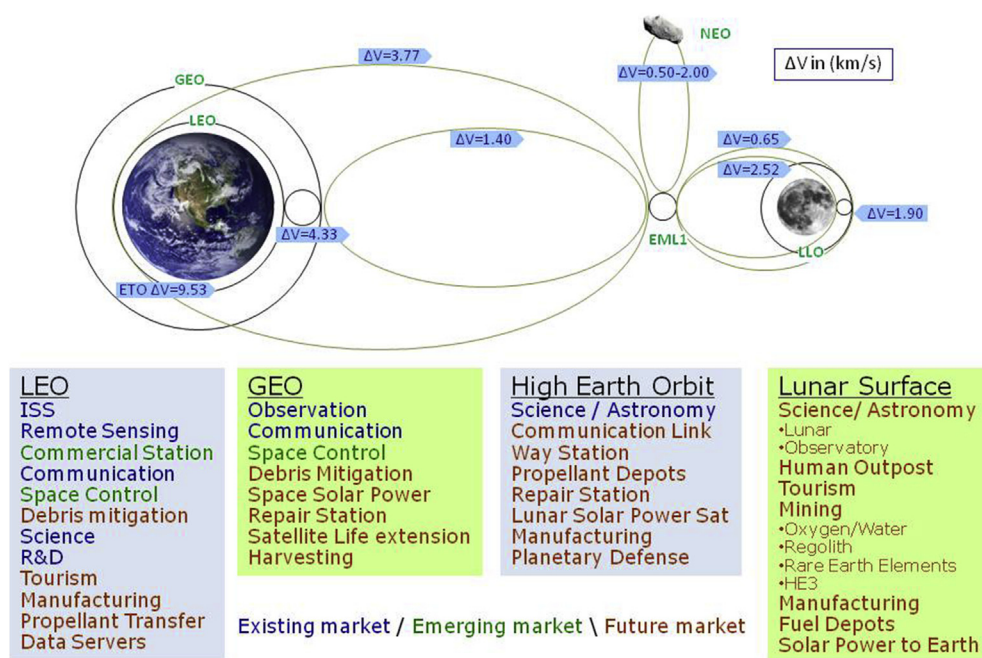


Fig. 1. The geography of cislunar space and potential economic activities that might take place in each location. Activities representing existing markets are in blue font, emerging markets are in green while potential future markets are in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transportation cost is to make use of space resources.

The geography of cislunar space is dominated by the gravity well of Earth. See Fig. 2. An enormous amount of energy is required to get from the surface of the Earth to LEO. This is the primary reason for the high cost. Once in LEO, much less energy is required to go anywhere else in cislunar space. This disparity nicely divides the transportation system into two segments: 1) Earth to orbit and 2) within cislunar space. There are many operational systems currently servicing the Earth to orbit market segment. All of them utilize some variation of a multi-stage chemical rocket. All are currently expendable although several companies are experimenting with various forms of partial reusability.

Once in orbit, the transportation problem becomes simpler in many respects, but new challenges are introduced. On the simpler side, the energy levels to be managed are much reduced and there are no aerodynamic forces to contend with. Some of the challenges include getting the system elements into cislunar space, reusability, finding fuel and the thermal environment.

Given the apparent availability of water from either asteroids or the Moon, it makes sense to base the cislunar transportation system on liquid hydrogen (LH2) and liquid oxygen (LO2). United Launch Alliance (ULA) has most of the world's experience operating LO2/LH2 propulsion systems in space. The second stage of both ULA's Atlas V and Delta IV launch systems utilize LO2/LH2 as propellant. Furthermore, the functionality of these stages is largely what is needed for the cislunar transportation system.

4. Transportation system elements and technologies

The next generation upper stage for ULA's Vulcan fleet of launch vehicles is perfectly suited to anchor the transportation for cislunar space. This stage is called ACES (see Fig. 3) [7], an acronym for Advanced Cryogenic Evolved Stage, and is expected to be available by 2023. ACES is 5.4 m in diameter and about 15 m long. It utilizes 68 tons of LO2/LH2 propellants and has a propellant to dry mass fraction of 0.92, exceeding the best in the world 0.90 mass fraction of Centaur, the upper stage for Atlas.

There are several advanced technologies that enable the utility of ACES as the cornerstone of a cislunar transportation system. First

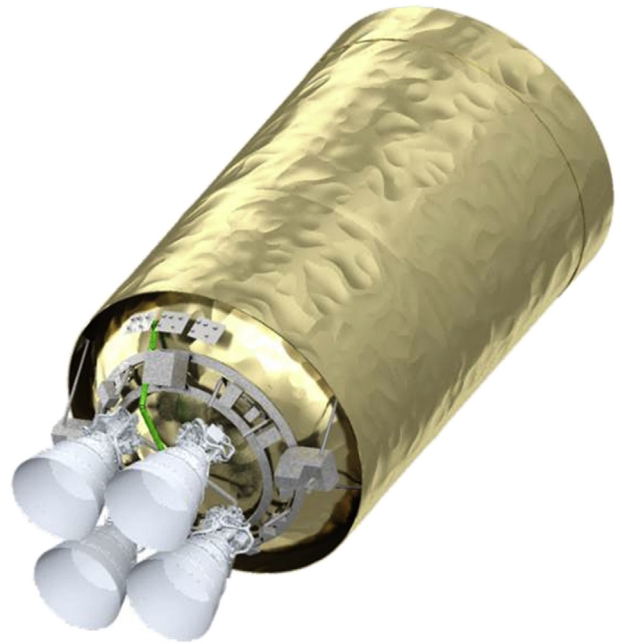


Fig. 3. Advanced Cryogenic Evolved Stage (ACES). ACES is the backbone of the cislunar transportation system. The stage utilizes LH2/LO2 propellants and up to four engines.

is Integrated Vehicle Fluids (IVF). IVF enables all the functions of the stage to be accomplished using just LO2 and LH2. This allows the stage to be fully reusable with refueling from propellants extracted from lunar ice deposits. Second are technologies for long duration storage of the cryogenic propellants. The basic ACES will reduce boiloff of the cryogenic propellants extending mission duration to a week or more, an order of magnitude improvement over Centaur. Storage in dedicated vessels, like tankers or depots, can be extended to years. Third is on-orbit transfer of cryogenic propellants essential for refueling. Finally, ACES can be equipped with a kit that transforms it into a lunar lander called XEUS (Experimental Enhanced Upper Stage).

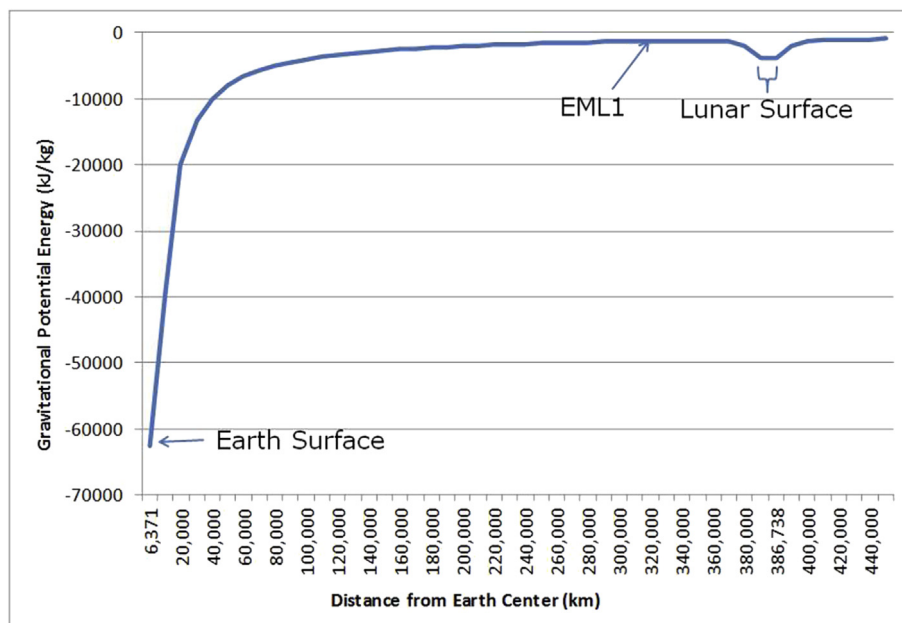


Fig. 2. Energy levels in cislunar space as a function of distance from the Earth's center.

4.1. Integrated Vehicle Fluids

Integrated Vehicle Fluids (IVF) is a technology that enables an upper stage to become a long duration in-space stage. A traditional upper stage utilizes at least four different fluids to perform its function. For example, the Centaur uses LO₂ and LH₂ as main propellants, helium to pressurize the tanks and hydrazine for attitude control. It also uses large non-rechargeable batteries for power. Helium capacity, hydrazine capacity and battery capacity all limit the life of the stage in terms of time and the number of times the main engines can be ignited. IVF removes all of these limitations. With IVF the only limitation to the life of the stage is LO₂/LH₂ propellants.

The core of the IVF system is a small internal combustion engine. See Fig. 4. This engine runs on hydrogen and oxygen gas from the ullage of the main propellant tanks. The engine is used to power a compressor which puts warm hydrogen and oxygen gasses back into the tank for pressurization. The engine also feeds gas through LO₂/LH₂ thrusters for attitude control and runs a generator for electrical power.

All of these components reside in a module located on the aft end of the stage. The ACES stage includes two IVF modules for redundancy.

4.2. Cryogenic storage

Current cryogenic upper stages like the Delta IV Cryogenic Second Stage (DCSS) or the Centaur are capable of missions of up to twelve hours in duration. One of the critical limiters is the loss of propellants via boiloff. At atmospheric pressure, LH₂ boils at –253 Celsius. LO₂ boils at –183 Celsius. In space, the heating environment is primarily due to radiation, the Sun being the main source. In LEO, radiation from the Earth becomes a significant source of heat as well.

ULA has leveraged its experience in cryogenic upper stages to develop a suite of technologies to eliminate LO₂ boiloff and reduce LH₂ boiloff by two orders of magnitude. These technologies have been developed over many years and verified in a series of tests at NASA's Marshall Spaceflight Center (MSFC) called CRYOTE. Fig. 5 shows the CRYOTE 3 test tank.

All of these technologies are passive, that is, they do not require any power to operate. Examples include design of the tank to reduce or eliminate penetrations or attachments, design of the tank to minimize the area of the hydrogen tank walls, enhanced multi-layers insulation, use of hydrogen boiloff to vapor cool warm spots and a common bulkhead between the LO₂ tank and the LH₂ tank with enhanced insulation. The later technology allows the

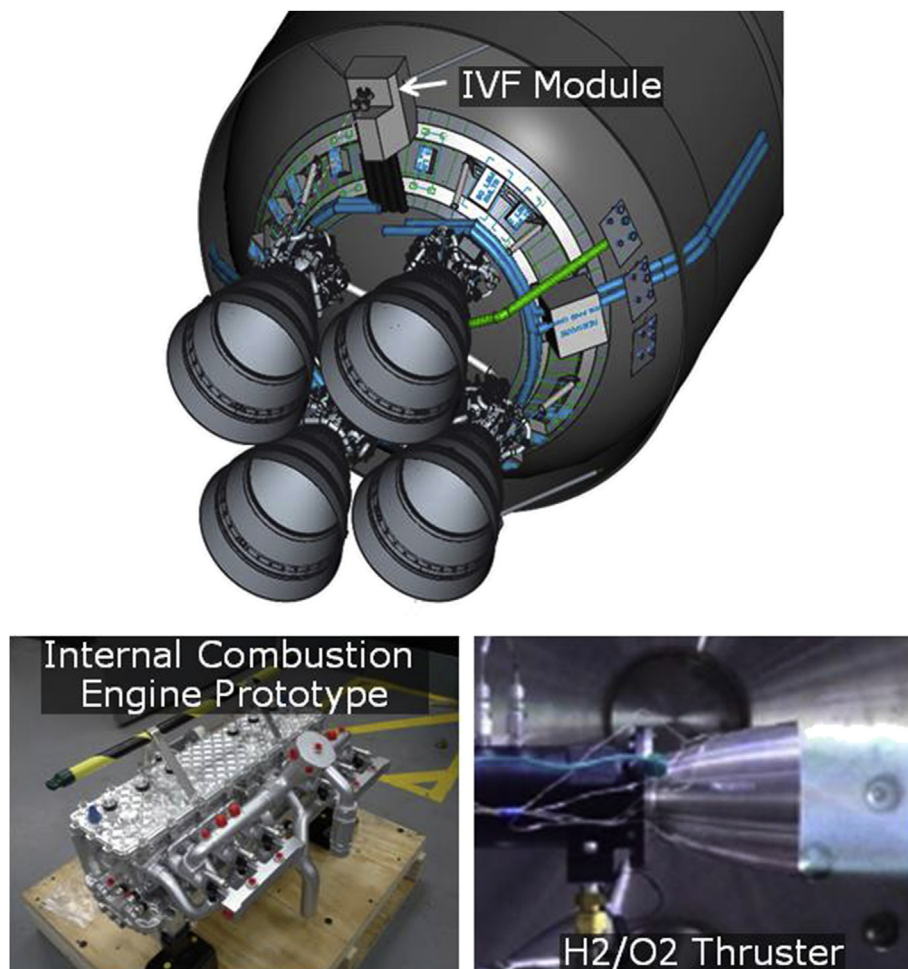


Fig. 4. Integrated Vehicle Fluids (IVF). The system consists of two modules located on the aft end of the ACES stage as shown in the top image. A prototype of the internal combustion is shown in the lower left image. A vacuum test of the hydrogen/oxygen thruster is shown in the lower right image.



Fig. 5. CRYOTE 3. A long duration cryogenic test bed. Shown is the three meter diameter, flight like propellant tank insulated for the initial phase of testing.

hydrogen to cool the oxygen and avoid oxygen boiloff. Boiling hydrogen is almost 10 times more efficient in removing heat than boiling oxygen.

These technologies combined enable ACES missions of up to a week without refueling, more than enough time to transit from EML1 to LEO and return. When these technologies are implemented into a dedicated long duration storage vessel (not a stage) and equipped with a Sun shield, storage times of years can be achieved.

4.3. Refueling

Having eliminated all fluids but LO₂ and LH₂, ACES is fully reusable if it can be refueled. The key technology for refueling is the

capability to transfer propellants from a storage vessel to ACES in space. This technology has been demonstrated and perfected in the CRYOTE test program [8].

The basic approach makes use of ULA's experience in transferring cryogenics under settled conditions, that is, under a small acceleration. This ensures the propellants are in a known position in the tank. The donor tank is pressurized above the recipient tank and flow begins. A small amount of propellant is lost to chill the transfer line to liquid temperatures. The recipient tank includes a "shower head" to create droplets. These droplets cool the gas in the empty recipient tank, reducing the pressure and creating a suction effect that results in a nearly 100% full recipient tank with almost no losses.

4.4. Horizontal landing

The ACES stage provides the backbone of the in-space portion of the cislunar transportation system. But to exploit lunar resources, we need a way to get large masses to and from the lunar surface. Fortunately, much of what is needed for a lander is already inherent in ACES. The main engines can bring the stage close to the surface, but a separate system is required for the final descent.

XEUS solves this problem by adding several banks of thrusters to the side of ACES to enable the stage to land in a horizontal orientation. The landing maneuver is vertical with respect to the lunar surface. See Fig. 6. In keeping with the overall architecture, these thrusters run off LO₂/LH₂ propellants from the main propellant tanks. The thrusters will require the addition of some electric pumps (powered by IVF). And landing legs will need to be added. Like ACES, XEUS is fully reusable with refueling.

5. An initial business case

Having established that the technology for a cislunar

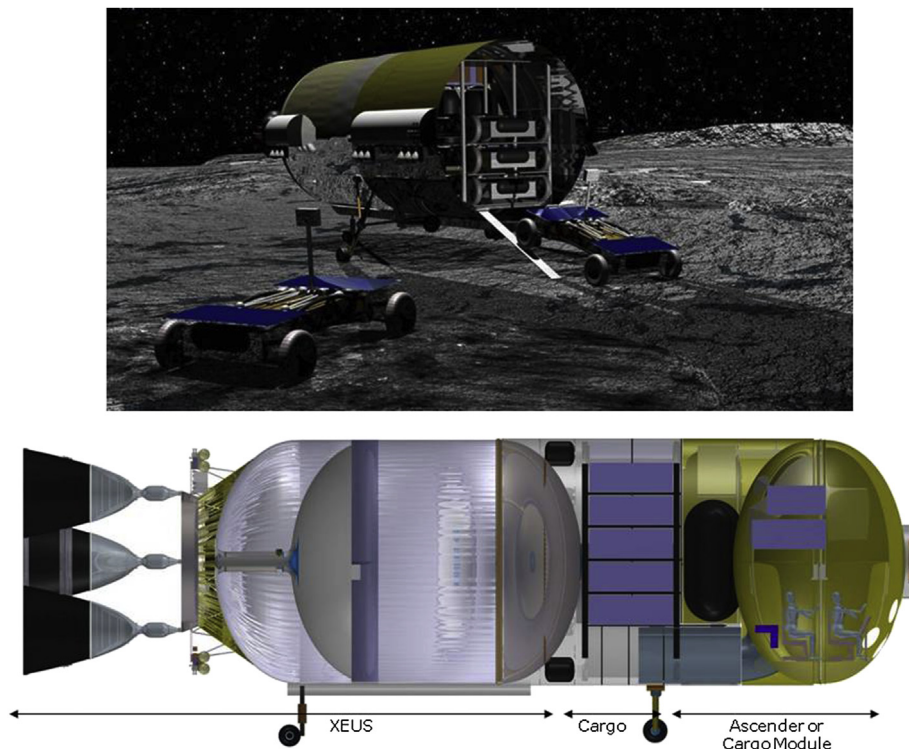


Fig. 6. XEUS, ACES derived lunar lander. The upper image is an artist rendition of XEUS deploying cargo on the lunar surface. The lower image shows a cross section of the stage with a crew module.

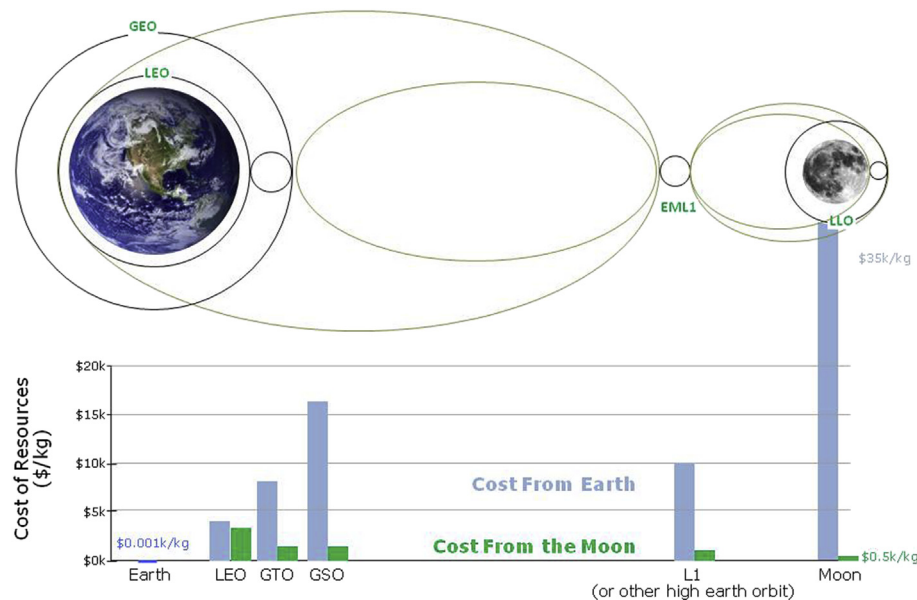


Fig. 7. Propellant costs at various cislunar locations. Costs for lunar sourced propellant are based on propellant in LEO at \$3 million per ton, to close the business case.

transportation system will exist early in the next decade, I turn my attention to the business considerations. Once the transportation infrastructure is in place, the cost of any activity in cislunar space will become drastically reduced. This is primarily due to the (presumed) availability of low cost propellant that does not have to be shipped out of the Earth's gravity well.

One great benefit of using ACES as the back bone is the possibility that the ACES stages could be operated in space after fulfilling a normal mission deploying a satellite. ULA's nominal flight rate is ten missions per year to a variety of different orbits. Normally the spent upper stage is disposed of either by re-entering the atmosphere or by putting the stage into a disposal orbit. In the cislunar economy, each of these stages can be reused over and over again. In the business case analysis, I've assumed that the hardware cost of the ACES is paid for by the initial satellite customer. The transportation cost using ACES in space is then the cost of ground based operators plus the cost of propellant. For this analysis, I've assumed the cost of ground based operations to be \$2 million per flight segment. A flight segment is defined as a round trip between two cislunar locations, e.g. EML1 to LEO and back.

Based on these assumptions an initial business case can be made to provide lunar-sourced propellant in LEO for ACES refueling. A fully fueled ACES in LEO can then be used to transport satellites from LEO to GEO. If the cost of propellant obtained from the Moon in LEO is less than the cost to ship propellant to LEO from Earth, the business case can be closed. Based on these considerations, a preliminary price point for propellant can be established. Fig. 7 shows a comparison of the cost of lunar propellant at various locations in cislunar space compared to the cost of propellant shipped from Earth. Note that the cost of LO2/LH2 propellant on the surface of the Earth is a negligible \$1/kg.

A price of \$3 M/ton in LEO will enable a launch company like ULA to reduce the overall price per kg to GEO by lifting a payload to LEO, then using ACES fueled with lunar propellant to take it from LEO to GEO. Since ACES and XEUS are used to transport the propellant from the Moon to LEO, price points can be established for propellant in other locations. For example, the business case is the same whether propellant is purchased in LEO for \$3 M/ton, or GEO for \$1 M/ton or at the Moon for \$0.5 M/ton.

To size the propellant mining operation on the Moon, I assume

three ACES trips from LEO to GEO per year. Each ACES requires 70 tons of propellant. Using ACES and XEUS, it takes about 4 tons of propellant to transport 1 ton to LEO. That means we need to produce 5 tons of propellant on the Moon for every ton needed in LEO. Finally, due to the fact that rocket engines burn LO2/LH2 propellants in a mass ratio of approximately 5.5 to 1 and that water comes in the ratio of 8 to 1, we need to mine about 1.5 tons of water for each ton of propellant. Putting this all together, to support 3 ACES flights per year, the plant needs to extract almost 1600 tons of water. The following table summarizes some of the key business parameters. (see Table 1).

6. Conclusion and next steps

The business case presented above makes no claim whether it is economically feasible to mine and process lunar propellants for \$500,000 per ton. My opinion is that it is quite challenging, though not impossible. One would have to be very clever about the choice of mining techniques as well as find very rich ice deposits. And these prices likely force a completely robotic operation. All costs significantly increase once humans are involved. However if propellant is available at that price, a business case can be made based on simply moving mass from Earth to GEO, which has been the staple of the launch market since inception.

There are a number of opportunities to improve the business case. For example, aerobraking in Earth's upper atmosphere can significantly reduce the propellant cost to transfer mass from the Moon to LEO. This could increase the allowable price on the Moon by a factor of two, dramatically improving the business case.

Table 1

Summary of some of the key business parameters for lunar propellant mining.

Tons of propellant delivered to LEO	210
Price in LEO	\$3 M/ton
Tons of propellant produced on the Moon	1050
Price at the Moon	\$0.5 M/ton
Tons of water mined	1575
Total revenue at Moon	\$525M
Total revenue in LEO	\$630M

Furthermore, if uses for propellant beyond LEO are found, the business case improves.

What we have shown is that there is some economic incentive to spur the creation of the first elements of infrastructure needed for a self sustaining cislunar economy. Once the transportation system is established, transportation costs will decrease enabling other business cases to close and other economic activity to commence. For example, once lunar propellant is available, the cost to launch mass to the surface of the Moon decreases by more than a factor of 2, improving the business case for a second propellant plant or any other lunar surface operation.

One application that has the potential to bring enormous economic benefit to people on Earth is space based solar power. It is estimated that a gigawatt space solar power station might require 12,000 tons of mass [3]. If launched from Earth, it would cost \$190B just for transportation. The use of lunar propellant would reduce the cost by 40%. If all the material for the power station was sourced from the Moon, the transportation cost drops to around \$6B. This puts it into the realm of feasibility for the \$6 trillion energy industry.

What are the steps to achieve this first piece of the cislunar infrastructure? ACES is currently under development by ULA as part of our product development strategy. Once ACES is operational, modifications for XEUS are very straightforward. There is much work to be done in terms of characterizing the nature and distribution of lunar ice deposits. Once the ice is characterized, mining strategies can be developed and tested. Demonstrator missions will then be launched to the Moon in preparation for full scale revenue bearing operations. Finally, investors and customers

must be found to initiate that first step. ULA is willing and eager to be one of those customers, purchasing propellant to fuel the transportation system.

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