IAC-24,D4,5,15,x80944

Industrializing the Earth-Moon System – the role of space mining and material processing for human civilization on Earth and in space

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Abstract

The Moon as well as the Near Earth Asteroids (NEAs) provide a great number of natural resources for mankind to utilize. The regolith layer on the lunar surface contains aluminium, iron, titanium and -last not least- helium-3, which can be used for future nuclear fusion. The lunar South Pole region contains also some quantities of volatile compounds like hydrogen, sulphur dioxide, formaldehyde, ammonia, methane, mercury and sodium. When metals are extracted from oxides we get oxygen as a by-product. Some NEAs contain metals like gold, platinum, nickel and also rare-Earth-elements. Others are carbonaceous asteroids with great percentage of carbon, water(ice) and even organic molecules. Combining the resources of our Moon and some NEAs we can provide building material for future space settlements. We can also produce space-made fuel for transportation. In addition some thousand tons of space debris orbiting Earth, such as decommissioned satellites and remaining rocket stages can be recycled. Favourite locations for space factories are the Lagrange Points of the Earth-Moon system, especially L4 and L5. We cover all of the above aspects of space mining and transportation and the design of industrial plants in space. Last not least we discuss some legal questions of space mining. Finally we propose a time-frame and a masterplan for the next decades to establish mining, industry and finally human civilization in space.

Keywords: Moon, Near Earth Asteroids, space debris, Lagrange Points, space mining

Preface

This paper has been created and written by humans. No Artificial Intelligence has been used, neither for the text nor for the figures.

Acronyms/Abbreviations

Artificial Gravity Manned Unit (AGMU)
In Situ Resource Utilization (ISRU)
International Space Station (ISS)
Lagrange Points (L1, L2, L3, L4, L5)
Lagrange Space Factory (LSF)
Low Earth Orbit (LEO)
Low Lunar Orbit (LLO)
Near Earth Asteroids (NEAs)

1. Introduction

To create a liveable environment for eight or nine billion humans on Earth we will have to utilize the natural resources of the solar system, especially those of our Moon and of the NEAs. When all mining and heavy industry is once established in space, our home planet can be turned into a "green paradise" without man-made pollution of air and water. The current energy crisis can be solved by developing nuclear fusion plants using helium-3, which is rare on Earth but abundant on the Moon. By using nuclear fusion anthropogenic global warming can be reduced effectively.

Unlike on Earth there are no limits to growth in outer space. In the long run we can build self-sustainable rotating space habitats with simulated gravity by the use of lunar and asteroid material, finally establishing human civilization in the solar system. In case of natural disasters like asteroid impacts, novae or super volcanoes extraterrestrial settlements will become a "life insurance" for the human species [1].

2. Lunar natural resources

2.1 Lunar regolith

Lunar regolith is a layer of broken rock which covers the bedrock of our Moon. It resulted from billion years of meteorite impacts on the lunar surface and is composed of mineral fragments, melt glasses and glass beads and agglutinates. The depth of the regolith layer is estimated to be between 4 and 5 meters in *mare* areas and 10 to 12 meters in the highlands [2]. The size of regolith particles varies from sub-micron to stadium-sized boulders on the surface, but most of the particles are below 1 cm [3]. The average bulk density is about 1.5 g/cm3 including the voids.

Table 1 shows the composition of Apollo soils smaller than 1 mm in oxide weight percent.

Table 1. composition of Apollo sample (weight percent) Apollo sample number 10084, split number 1591 [4].

SiO_2	41.3 %	quartz
TiO_2	7.5 %	titanium oxide
Al_2O_3	13.7 %	corundum
Cr_2O_3	0.29 %	chromium oxide
FeO	15.8 %	iron oxide
MnO	0.21 %	manganous oxide
MgO	8.0 %	magnesium oxide
CaO	12.5 %	lime
Na_2O	0.41 %	sodium
K_2O	0.14 %	potassium
Total	99.8 %	

2.2 Helium-3 (He-3)

He-3 is a rare isotope of helium on Earth that has many important uses, including low-temperature physics research, medical lung imaging, neutron detection and potential nuclear fusion [5]. Fusing Deuterium and He-3 to He-4 + protons releases 18.3 MeV of energy per reaction [6]. According to Wittenberg et al. [7] the Moon contains approx. one million tons of He-3, implanted into the lunar regolith by the solar wind. If regolith is heated to extract all volatiles, the evolved gases can be compressed and separated. He-3 can then be brought to Earth or to industrial plants in space as a liquefied gas [8].

2.3 Water on the lunar South Pole

Some craters of the South Pole region have permanent shadowed areas with a temperature ranging from 40 to 100 °K. At least hydrogen molecules could be trapped in these areas, but also sulphur dioxide, formaldehyde, ammonia, methane and others. In 2009 NASA´s LCROSS mission detected water ice in significant quantities in the permanently shadowed *Cabeus* crater [9]. It is estimated that about 5 % of the targeted crater´s soil consists of water ice [10].

3. Near Earth Asteroid resources

Within the last decades approx. 18,000 NEAs have been detected and their number is still increasing. Their sizes range from several meters to some hundred meters or even kilometers in diameter. There are three main classes of NEAs, the *Amors*, the *Atens* and the *Apollos* [11]. The Amors are orbiting the Sun beyond Earth´s solar orbit, whilst the Atens can be found in a region closer to the Sun and approaching Earth by 0.983 AU (Astronomical Unit = average Sun-Earth distance, 150 million kilometers). The Apollos are the most numerous group of NEAs and differ from the Amors in their minimum distance from the Sun, which is about 1.017 AU. Some of them may intersect the Earth´s solar orbit and cause collisions. On one hand we will have to develop methods of detection and deflection techniques for hazardous NEAs, on the other hand we can use these technologies to modify their orbits and exploit their natural resources. Modifying the solar orbits of asteroids, forcing them e.g. from a solar orbit into an Earth orbit beyond the Moon, can be done by the use of future nuclear fusion rocket engines as mentioned in *2.2* [12].

3.1 Mineralogy and physical properties of NEAs

Geochemical analysis of meteorites found on Earth shows typical groupings of elements [13,14]. One group are the “siderophile elements” that are related to nickel-iron. The second group is related to iron-sulfide, characterized by the “chalcophile elements”. A third group are the “lithophile elements” related to oxygen, enriched in the silicate parts of meteorites and asteroids. Table 2 shows the geochemical groups for meteorites with typical elements occurring in mineral associations. We can find numerous metals and rare-Earth-elements we need for space-based industry and on Earth.

Table 2. geochemical groups for meteorites/asteroids

Group	Elements (selection)
Siderophile	Fe, Ni, Co, Cu, Au, Pd, Pt, Os, Ir
Chalcophile	Fe, Ag, Cd, In, Th, Pb, Bi, S, Se, Te
Lithophile	Rb, Cs, Be, Al, Sc, Th, U, Ti, Nb, Ta, Cr, Mn, rare-Earth elements

3.2 Potential asteroid mining and utilization

In a previous study [12] we took the asteroid 2008EV5 as an example for a mining concept. This celestial body is a typical Aten group asteroid with a mean diameter of 450 meters. It belongs to spectral type S (stony asteroids) and is supposed to have an average bulk density of 3 g/cm3. We assume the asteroid having a metal core and a silicate mantle and crust with an estimated mass of about 140 million tons. To reach the metal core we have to drill a tunnel to the centre of the asteroid. First of all a *manned mining station* is docked to the asteroid (Figure 1). It contains a tunnel boring machine (red), conveying and processing machinery (yellow), storage and docking modules (blue) and rotating habitat modules (green) which provide simulated gravity for the crew. Electric current is provided by solar panels and a nuclear battery. The tunnel boring machine must work slower, smoother and more precisely than in a terrestrial mine, not to disturb the structural stability of the asteroid rock. It drills a central tunnel of 8 meters in diameter to the metal core of the asteroid and then excavates step by step a spherical cave up to 50% of the asteroid´s volume.

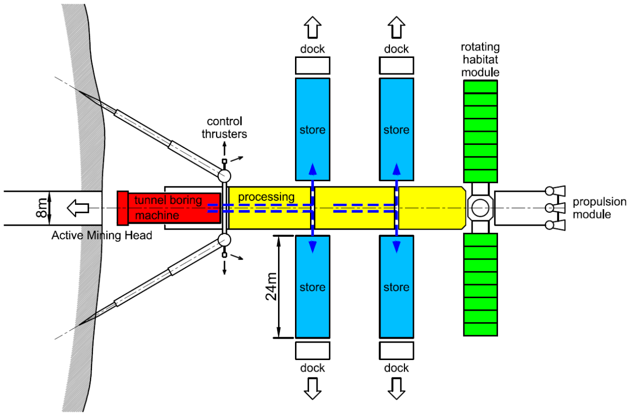

Figure 1: manned mining station for asteroid mining (schematic) by W. Grandl and A. Bazso 2013

The remaining hollow celestial body can be used for storage or even to build a human settlement inside the cave in the long run. In the manned mining station the ore is partially processed and prepared for transport. Unmanned automated cargo spaceships transport the material to metallurgical plants and space factories in the Lagrange Points of the Earth-Moon system for further processing.

4. Orbital debris as a resource for space-based industry

In a recent study A.V. Autino et al. have described orbital debris as a great future business opportunity [15]: ESA´s Space Debris Office estimates that there are about 36,500 objects larger than 10cm, 1 million objects between 1-10cm and approx. 130 million objects 1 mm to 1 cm. The highest concentration of man-made space debris is in LEO and poses a great threat to operating satellites, launchers and space stations. It is urgent to develop techniques of collecting and reprocessing orbital debris in space. Whilst small debris will be hard to collect the focus lies on the objects larger than 10cm. NASA considers e.g. pulse lasers to change the velocity and the flight track of objects and physical "sweepers" to collect small particles. Given a space factory in situ various products can be made of collected debris such as rocket propellant or metal powder for 3D printing. Several large objects like rocket upper stages and fuel tanks can be reused for storage or the building of big structures in space.

5. The Lagrange Space Factory (LSF)

The favourite locations for an initial space factory are the Lagrange Points of the Earth-Moon system. There are five Lagrange points which provide an equilibrium between the gravity forces of Earth and Moon. Especially in the points L4 and L5 an object remains in a stable position because there is a triangle between the object, the Earth and the Moon. Building the first space factory e.g. in L5 will enable us to process material and produce goods in zero gravity (Figure 2). In a first stage the LSF will process orbital debris from Earth orbit and lunar material. In 1976 Gerard K. O´Neill has proposed an electromagnetic mass driver which catapults containers filled with regolith into lunar orbit or to L1 [16].

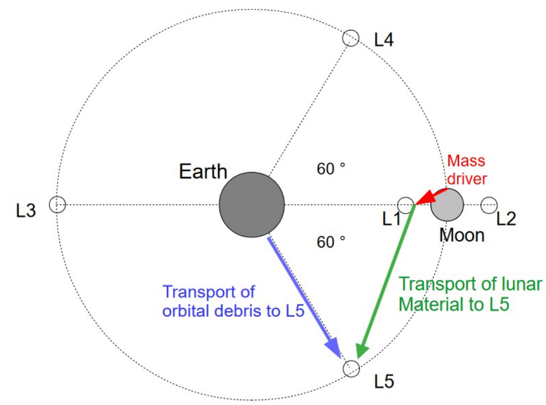

Figure 2: the Earth-Moon system and its five Lagrange points; a LSF in L5 is in a stable position

5.1 The LSF preliminary design

The structure of LSF is designed modular and can be extended along its major (longitudinal) axis. It starts with the rotating Artificial Gravity Manned Unit (AGMU) for a crew of 48 persons. This initial part of LSF contains eight rotating living quarter modules providing 0.9 g, four zero-g central modules, a docking module, connecting tubes and structural framework (Figure 3).

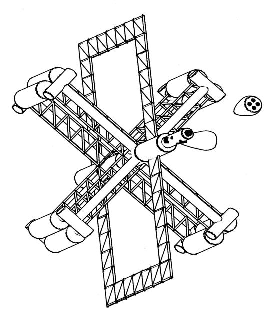

Figure 3: AGMU (derived from the project AGOS Artificial Gravity Orbital Station [17]), length 78 m, span 102 m, rotation rate 4.2 rounds per minute

For transport of the modules from Earth to L5 we propose the use of SpaceX Falcon launchers with reusable first stage.

In a second step a triangle-shaped structural framework is added to the initial station. In the centre of this linear structural framework a central communication tube of 7 meters diameter is built. This tube is connecting all parts of LSF and is equipped with wiring cables, pipes and plumbing units. Step by step factory units are built and connected to the central framework, each one 54 m long and 24 x 36 m in diameter. Each factory unit has a volume of 46,600 m3 and can be equipped with different machinery in a zero-g environment. The central framework, the communication tube and the factory units are non-rotating and have docking facilities for cargo spaceships (Figure 4, Figure 5).

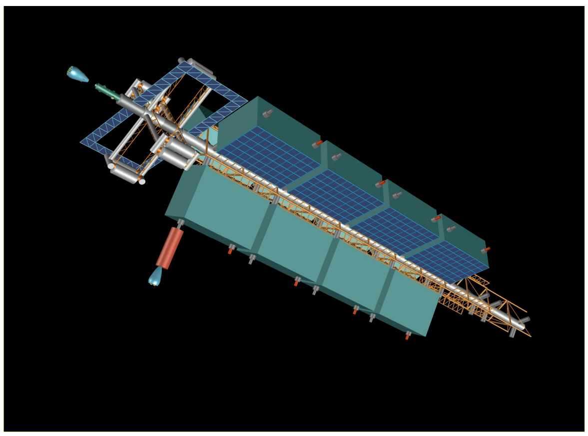

Figure 4: LSF design: 12 factory units fixed to a central structural framework, the initial AGMU for the crew on the left side, the red cargo spaceship is docking

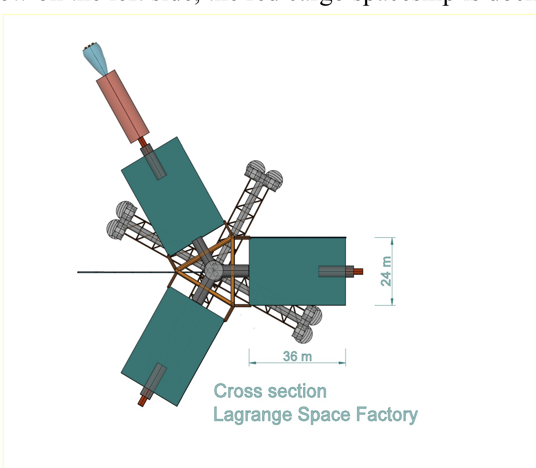

Figure 5: LSF cross section: factory units(green), central framework (orange), cargo spaceship (red), central communication tube and rotating AGMU (grey)

5.2 Transport of material and industrial production

A fleet of unmanned cargo spaceships is shipping raw material, regolith from the Moon and ore from NEAs to LSF. Some of the factory modules contain metallurgical plants, others are equipped to produce oxygen and other gases. Additional raw material is made by processing orbital debris. On the lunar surface raw material can be packed into cargo containers and catapulted from lunar surface to LLO or to L1 by an electro- magnetic mass driver. The robotic cargo spaceships transport the containers from lunar orbit and L1 to the LSF.

Various industrial products and semi-finished goods will be produced in a zero-g environment, such as tubes, trusses and sheets of steel and aluminium, with oxygen as a by-product of regolith-processing. Regolith and industrial slag can be pressed and sintered to bricks. Rare materials like gold and platinum will be extracted from asteroid ore. Last not least orbital debris as an in situ resource (ISRU) will be recycled to produce metal powder for 3D-printing among other high-tech products. The goal is to produce building material for future human settlements in space, propellant, oxygen and water on a large scale.

5.3 The economy of LSF

Planning and financing of the basic structure should be done by private public partnership. The basic structure contains the AGMU, the central framework and the communication tube plus nodes, fittings and plumbing. The particular factory modules may be financed and constructed by private companies and docked to the central framework (Figure 6). Due to its modular structure the LSF can be elongated easily to increase and diversify industrial output. Industrial processing, manufacturing and transport in zero gravity will be done preferably by Artificial Intelligence and robotic machinery, supervised by a human crew of engineers and specialized craftsmen.

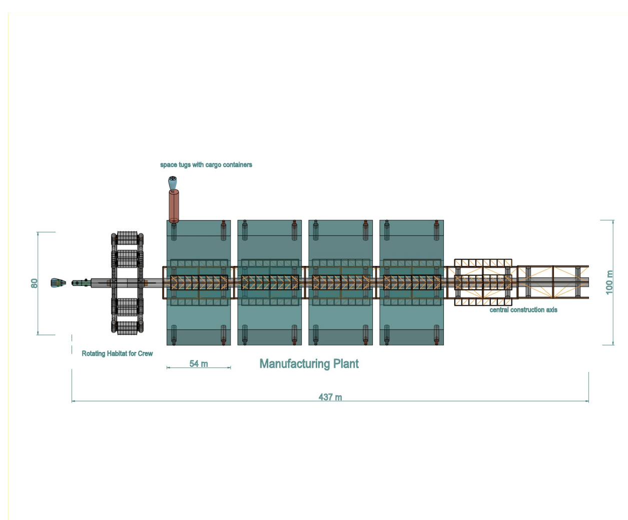

Figure 6: LSF side view (X-ray): the structure can be extended along its central axis

6. A proposed time-frame

Any assumption of a possible masterplan for the building of large structures in space such as the proposed LSF depends on some important precursory steps as follows:

-A new orbital station in LEO (succeeding ISS) preferably with simulated gravity	2035
-A manned lunar base including ISRU and an electromagnetic mass driver	2040
-LSF *first stage* to process lunar material and debris from Earth orbit	2045
-Mining of NEAs, advanced propulsion technologies (e.g. nuclear fusion engines)	2060
-LSF *additional stages* to process asteroid ores and conglomerates	2065

The dates we have assumed above strictly depend on international cooperation and accurate political decisions of all space faring nations. Last not least some legal questions will have to be answered. According to present space law celestial bodies can be owned neither by a nation nor by a private company. The proposed mining of the Moon and NEAs could be done by private companies with a limited licence to exploit e.g. a certain area of the Moon within a definite period.

7. Conclusions

Our solar system with its planets, moons and asteroids provides enormous natural resources to be harvested and utilized by humankind. Cislunar space -the region of the Earth-Moon system- will be the primary target for space industrialization and human settlement. Efficient space flight with reusable rockets on a large scale would signify an essential and giant leap forward in the development of vital activities beyond the productivity of the planet Earth. The money for big space enterprises may be found in the enormous amount of capital and know-how set free by a partial disarmament policy (A.Germano,W.Grandl 1993 [18]). Opening the gate to extraterrestrial resources can help to avoid the struggle for terrestrial resources between different nations. The industrialization of cislunar space could become a key factor of disarmament and peaceful international cooperation. In the long run all mining and heavy industry could be shifted into space to minimize pollution and climate warming on Earth. In the centuries to come humans will settle on Mars and even beyond, becoming an "interplanetary species" (E. Musk).

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