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Viewpoint

Biomining and methanogenesis for resource extraction from asteroids

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ABSTRACT

Biotechnological resource extraction methods such as biomining and biogas production could fill a vital niche in currently proposed ways for extracting minerals and producing fuel on asteroids. Well established on Earth, biomining applications on asteroids could significantly increase the output and efficiency of minerals processing. Biogas production, unlike conventional fuel extraction processes, relies on the presence of carbonaceous chondrite on asteroids. Bacteria placed on or within the asteroid would ferment these carbon sources and methanogenic Archaea would produce methane for spacecraft propulsion and industrial applications. Supporting microbial communities in space requires a thorough understanding of the limitations of microbial life, interacting environmental parameters as well as factors such as asteroid structure and nutrient availability. This paper examines engineering and ecological principles required to support an asteroid based microbial community. In addition socioeconomic factors such as current space policy and potential economic prospects are also discussed. Biotechnology is increasingly filling a niche in conventional engineering; with the advent of a new era in space, evolving these technologies is vital to fully developing humanity's space faring capabilities.

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1. Introduction: potential of biological resource extraction in space

Asteroid mining in itself has significant potential in terms of ensuring the future of human spacefaring capabilities [1,2]. Biotechnological resource extraction processes such as biomining and biogas production have the potential to further this goal. These processes are currently successfully utilised on Earth. Biomining (microbially based mineral extraction processes) is responsible for approximately twenty percent of global copper and five percent of global gold production [3]. Similarly, advances in biogas production are being increasingly applied across the globe [4,5]. Current space missions rely on predetermined fuel reserves, these having been carefully optimised to minimise launch cost and maximise payload capability. Large-scale, space-based industries would need to rely on *in-situ* resource acquisition as resupply from Earth is neither practical nor economically feasible. The implementation of *in-situ* fuel and material production processes is integral to the development of such an industry.

Whilst biotechnological metal extraction is reliant on the presence of specific ores contained within asteroids, biogas would have to be fermented from the existing chondrite. One possible source of *in-situ* production for hydrocarbon-based fuels is found in carbonaceous asteroids, where biogas could be produced via methanogenesis. Liquid methane (LCH_4) fuels have significant advantages over conventional fuels such as liquid hydrogen (LH_2). These are primarily due to the higher density and lower storage volume requirements for LCH_4, resulting in a more efficient rocket fuel [6]. The higher cryogenic temperature of LCH_4 allows for similar boiling points between methane and oxygen, 109 K and 90 K [6] respectively, resulting in lower storage complexity. In addition, the LOX/LCH_4 mixture allows for a non-toxic and clean combustion process [6]. Due to the various applications for a methane-based fuel source in thruster technology and for industrial applications, a range of markets could be readily exploited.

Earth-based applications of biomining and biogas production are filling an ever-increasing percentage of production capabilities.

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On Earth, these are being driven by environmental concerns and decreasing fossil fuel reserves. Biomining processes are being successfully employed, utilising a range of ferrous iron-oxidising bacteria and sulphur-oxidising bacteria, with an increasing number of strains showing suitability in emerging metal extraction fields [7]. Biomining is currently being successfully utilised in the extraction of copper, gold, iron, nickel, chromium, cobalt and manganese [3,8], all of which have a potential use in an emerging space-based industry.

Whilst biomining and methanogenic reactions are well established on Earth, the effects on these processes in outer space are unknown. The issues that arise cover several disciplines of science as well as engineering, and require an understanding of environmental parameters, microbial physiology, ecology, asteroid characteristics and the effects of refining processes. Whilst these fields will govern the feasibility of conducting these types of missions in space, there are further aspects that require detailed analysis such as economic, legal and ethical parameters.

2. General considerations

Biomining techniques could prove more practical than conventional mining techniques in extracting resources from asteroids. Biomining presents a unique challenge as it relies on the activity of microbes in the hostile space environment. The microbes would need to be able to occupy what is a narrow ecological niche. The NASA-led Asteroid capture mission has identified likely places to situate an asteroid for further study. Locations and orbits of note include the Earth–Moon Lagrangian points as well as other specific lunar and Earth orbits [9].

As initial asteroid-biomining ventures would potentially be applied to these near-Earth, factors to consider should include not only general solar system effects, but also those dealing specifically with near-Earth conditions. Of particular concern for these situations are the effects dealing with radiation, pressure and gravity. The effects of radiation on microbes would have to take into account galactic cosmic radiation, solar cosmic radiation and Van Allen belt radiation. The pressure levels of artificial environments designed for these operations can directly affect microbial physiology and development, as well as have significant impact on the stresses experienced by the external structure. Microgravity, arguably one of the most analysed in-flight effects by means of ground based analysis, plays an important role [10]. Drop tower testing, parabolic flights and clinorotation-based model-reduced-gravity are some of these analysis methods. A sound understanding of these parameters and their synergistic effects in these proposed environments is key for determining bacterial growth and the optimisation of a support system.

Specific case scenarios also need to be understood, one such case being the composition and rotation of asteroid 1950 DA [11,12]. The make-up of 1950 DA consists of a loose collection of rubble and as such could act as a natural layer of protection from the otherwise lethal space environment. Whilst the physical behaviour of these asteroids traditionally has been viewed using gravitational and frictional forces, it has now been realised that cohesive forces could explain the fast rotation speeds of rubble-like asteroids [11]. The high surface-area-to-volume ratio of this type of asteroid would allow biomining to be a potentially preferred method of metal and bio-gas extraction over conventional mining techniques. In addition, novel concepts such as the gas-filled enclosed asteroid retrieval method, described in Ref. [13], could be used to stabilise the asteroid, thus optimising it for mining operations. Further uses of this technology could lead to an adaptation for microbial communities; such a system could ensure the right environment for mining operations and the consequent optimisation of this environment for the necessary microbial consortia.

3. Environmental parameters permitting microbial activity

Bacteria and archaea are known to inhabit some of the most hostile environments found on Earth. These environments encompass the cold-desert soils of Antarctica, hydrothermal vents, deep ocean subsurface fossil fuel deposits, acid mine drainage as well as the paleosols with dry frozen microenvironments [14–17]. So-called extremophiles not only survive, but also thrive when subjected to extreme physical and geochemical conditions. They have demonstrated an ability to adapt to one or more extreme parameters as they exploit a remarkable diversity of energy and elemental resources. In order to sustain life and flourish on asteroids, viable microbial communities need to tolerate extremes in temperature, low pressure, desiccation, high radiation, an anoxic environment and potential alkaline and/or acidophilic pH habitats [18]. Celestial bodies such as asteroids share many similarities with the extreme conditions found on Earth. Temperature is a key parameter of sustained life, with microbial thermal preferences ranging from hyperthermophilic (>80 °C) with a maximum of 113 °C [19–21] to psychrophilic (<−15 °C), minimum −18 °C [18]. Cold-adapted bacteria and archaea can survive and reproduce below the freezing point of water with temperatures ranging from 2 °C to −28 °C [22–25]. Significantly lower metabolic activities have been observed as low as −40 °C, suggesting a possibility for the existence of even lower microbial growth temperatures [26]. Psychrophilic microorganisms living in the permafrost soils and sea ice are often exposed to an anoxic atmosphere and high radiation doses [23]. *Deinococcus radiodurans*, for example, can withstand ionizing radiation up to 20 kGy of gamma radiation and UV radiation up to 1000 J m^{-2} [27,28], demonstrating incredible radiation resistance. In addition, *D. radiodurans* proliferates under extreme freezing, desiccation and nutrient-limited conditions [27]. The adaptation of microorganisms to high-pressure conditions is well documented, however little is known regarding the effects of low-pressure environments on microbial cells. Decreased survival of microbial cells exposed to space vacuums has been identified [29,30] with the primary process affecting microbes in space being vacuum desiccation [31]. *D. radiodurans* has been documented to have a remarkable resistance to high-strength vacuums as low as 10^{-5} Pa [32], making polyextremeophiles ideal candidates for survival in the space environment. Microbes adapted to a broad pH spectrum are known, with numerous bacteria and archaea thriving at an optimum pH from 0.7 to 3 [22,30,33–35] as well as at pH values greater than 10 [23].

Extreme temperatures, radiation, pressure, and pH conditions can denature and/or damage microbial proteins, nucleic acids and lipids [18,36]. The plasticity of microbial genomes allows Bacteria and in particular Archaea to adapt to a wide spectrum of extreme environments [23,37]. Microbes have successfully confronted the physical challenges with developed protection strategies like specific DNA repair mechanisms, cold-adapted proteins, high levels of molecular antifreeze compounds, modification in the cell structure (decreased membrane fluidity and reduced enzyme activity), altered transport of nutrients and waste products and the ability to form large cellular aggregates against extreme cold [23,25,27].

Permafrost and arctic regions are promising locations for the isolation of microorganisms intended for use on asteroids. Terrestrial microbes could potentially thrive on asteroids if strategies for overcoming water and nutrient deficiencies were addressed. As for all life, microbial cells require water to conduct any metabolic activity [18,38]. The ability of microbes to live within rocks and generate a subterranean biosphere suggests that life can exist without light or external nutrients [39–41] but the existence of

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