Space Mining

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Humans to Moon and Mars Seminar

22 October 2019

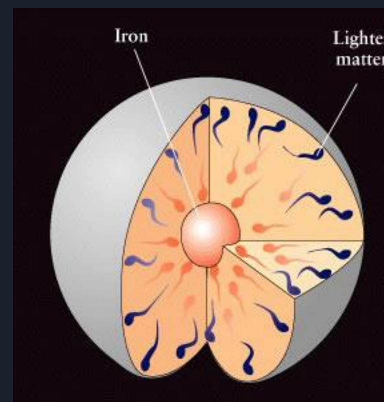
Outline

1. Why Space Mining?
2. How Does it Work?
3. Legal Aspects (yes, the one you've all been waiting to chime in on)
4. Economic justification
5. Other implications

Why mine in space?

Why mine materials in space?

- During Earth's formation, dense siderophile elements sank into the mantle and core
  - Earth's crust is quite depleted in transition and rare earth metals
  - Small asteroids have insufficient binding energy to undergo differentiation
- Estimated 2 trillion Mg of water on near earth asteroids [Planetary Resources]
  - This can be used to establish propellant and supply depots in cislunar orbit



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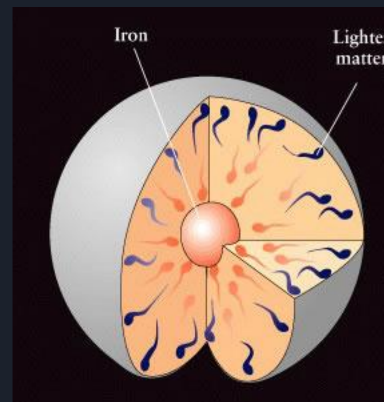

Though initial asteroid mining efforts will emphasize harvesting water for in situ resource utilization (ISRU), extraction focus will shift to mineral and metal extraction as infrastructure and technology develop.

Space Resource Utilization

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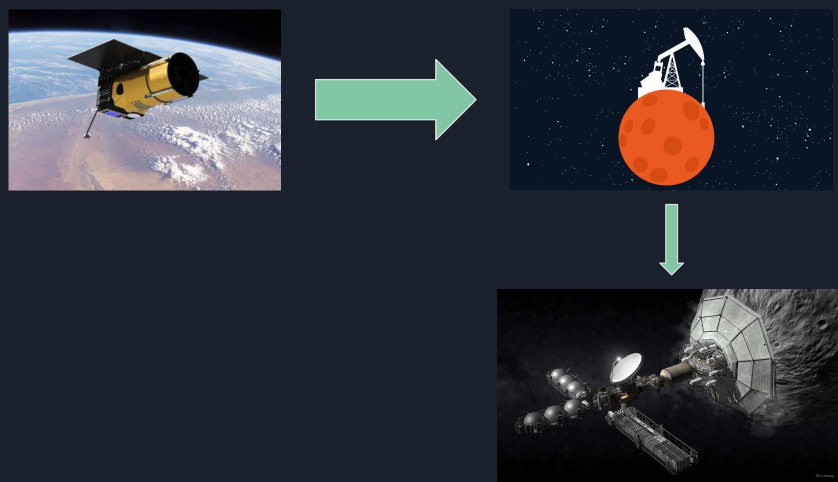

Space Resource Utilization

ISRU

"The single most important development that is required for enabling, sustained human presence on the Lunar surface is having the capability to extract oxygen, water, and metals from the Lunar regolith [Mclemore, 2008]."

- Oxygen/water: life support and propellant production
- Metals: in situ manufacturing

Spare parts cannot be supplied ahead of time for unexpected failure modes. An in situ manufacturing capability:

- Reduces downtime due to failed components
- Decreases by recovering quickly from degraded operation of equipment
- Improves system flexibility
- Enhances crew safety

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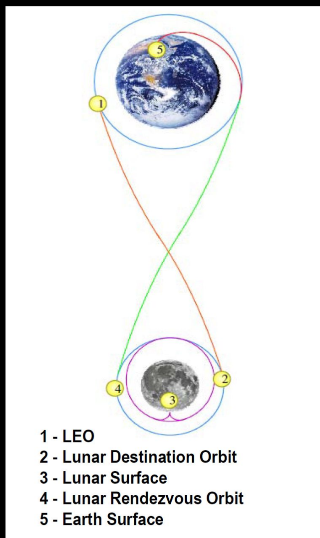
ISRU is a vital component of NASA's human exploration architecture.

Gear Ratios for Various Architecture Waypoints [Lightfoot, 2012]



A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO
LEO to Lunar Orbit (#1→#2)	~4.3 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	~7.5 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module)	~9.0 kg
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Earth surface to LEO – ~20.4 kg

Earth surface to lunar surface - ~153 kg

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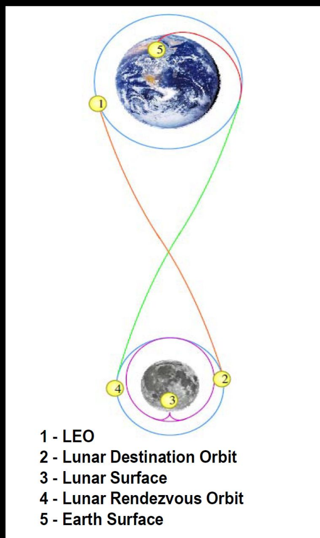

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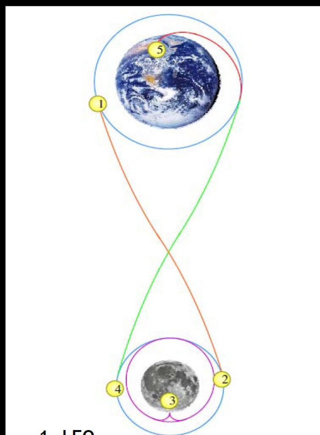

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Robust, regenerable ISRU systems have the potential to vastly decrease launch costs.

How? The Technology

How much material is needed?

- NASA is sizing ISRU technologies to provide up to 1000 kg of metals per year
- The primary metals that are both of interest for in situ manufacturing and can be found locked into oxides in the Lunar regolith are iron, aluminum, magnesium, calcium, and titanium
- 10 Mg of oxygen per year

State of the Art: Molten Oxide Electrolysis (MOE)

- Regolith is melted and then electrolysed
- Process requires temperatures of 1400 - 2000 C
- High power requirements, safety concerns, material compatibility issues, heavy iridium electrodes [Karr, 2018]

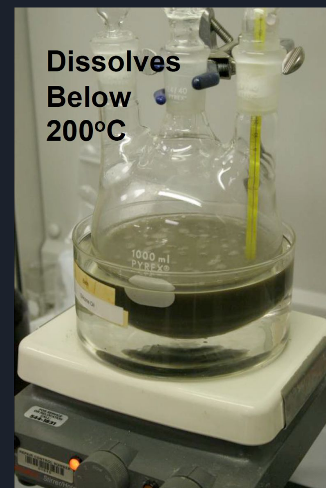
Chemical Solvation

Ionic Liquids (ILs)

- Organic alts with melting temperatures below 100 C
- Relatively large liquid temperature range
- Negligible vapor pressure
- Electronic stability
- Non-toxic
- Organic, so functional groups can be tuned [Nancarrow, 2017]

Process [Marone, 2009]

1. Solubilization of regolith in IL medium to convert metal oxides to water and metallic ions
2. Electrolysis of water produced to generate oxygen and hydrogen
3. Electrolytic metal extraction
4. Regeneration of IL medium using hydrogen gas electrode



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IL oxygen and metal extraction is safer, less expensive, and less energy intensive than MOE.

Volatile mining (ISRU)

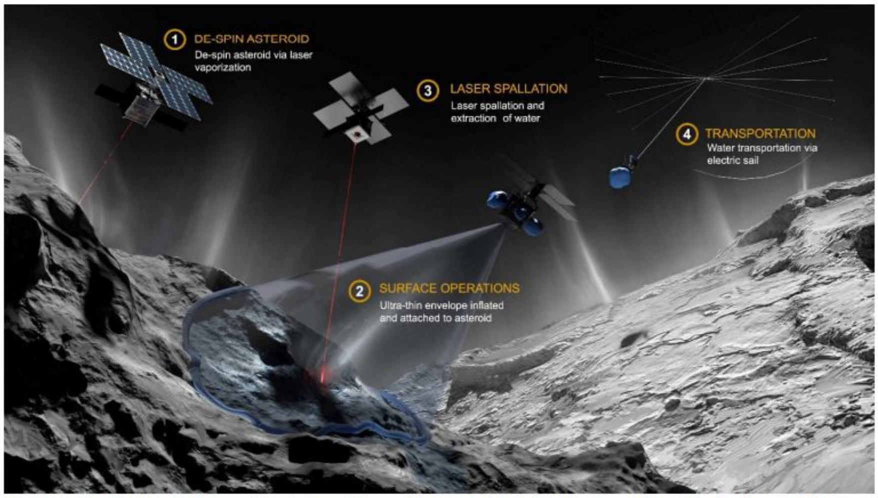


Figure 7: Small spacecraft asteroid volatile mining architecture using lasers for extraction and electric sails for transportation (Image credit: Efflam Mercier)

https://arxiv.org/ftp/arxiv/papers/1810/1810.03836.pdf - A Techno-Economic Analysis of Asteroid Mining, Hein et al.

Space Biomining

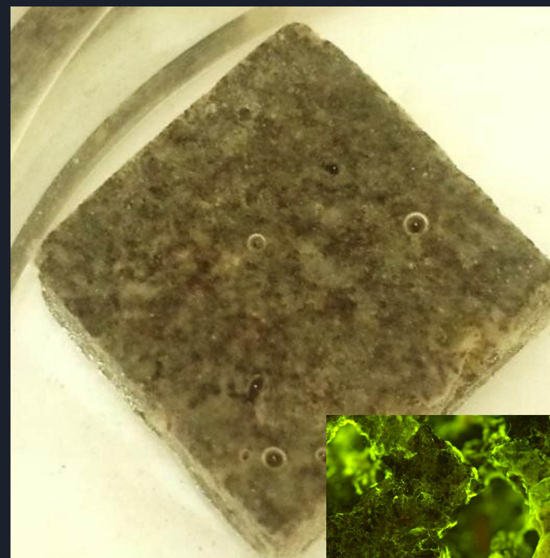
- Microbes to leach out minerals from rock
- Not as chemically intensive, or toxic
- Can share enabling mass requirements with life-support systems
    - Lighter/Cheaper?
    - Will still need conventional systems for final stages of extraction
- Research being pioneered in-house (At CU!)

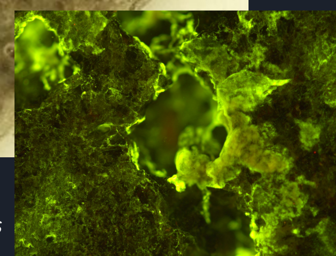
BioServe Space Technologies · University of Colorado Boulder · CSIRO · CROW Industries

Picture reference:
https://phys.org/news/2019-07-harnessing-power-microbes-space.html

Space Biomining

- 15% of Copper, 5% of Gold already mined this way on Earth
- Preliminary investigations underway using BioServe's Fluid Processing Apparatus (for culture)
- Substrate rock (on Earth - using various simulants)
- BioRock flight modules investigating BioFilm formation
  - Adhesion
  - Metabolic efficiency in microgravity
  - Using Basalt (vesicular nature - greater surface areas)





Sphingomonas desiccabilis

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Current State | Sample Return Missions | Hayabusa (and others)

- 2005 rendezvous with Itokawa, intended to shoot pellets at surface and capture ejecta during brief "landing"
- Lots of failures
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Osiris-REX will return >2kg for ~$1B

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#HumanSpaceflightFTW

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#HumanSpaceflightFTW

Or meteorites

ARM (Asteroid Redirect Mission) - now defunct

Asteroid Redirect Mission: https://youtu.be/lCJjTJZSFMg (From 00:30 to 4:06)

https://solarsystem.nasa.gov/asteroids-comets-and-meteors/asteroids/16-psyche/in-depth/

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Lessons from space missions

- Rosetta's Philae Lander:
    - Problem: comet escape speed is only ~1 m/s
    - Solution: Harpoons (should have) fired into surface to hold it there, but the landing site was much softer/finer-grained than predicted, so they failed
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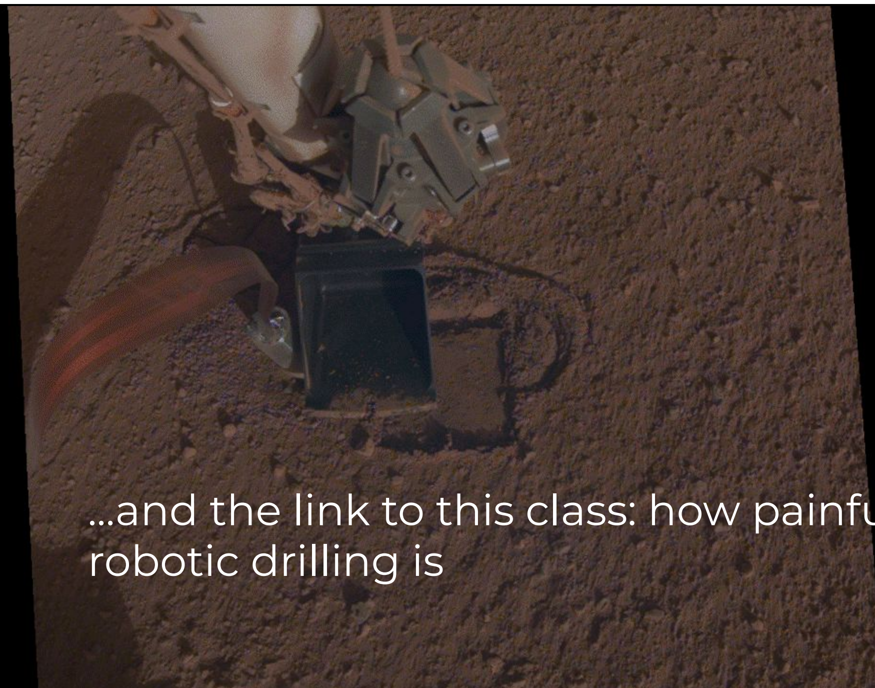
- Insight's Mole:
  - Problem: Martian soil is too smooth for drill to catch, so it has only gone ~35 cm out of 5 m goal
  - Solution: Push on it with the soil scoop, to increase normal force, and hence friction.
  - Consequence: techniques that work on Earth do not necessarily work on other bodies



...and the link to this class: how painfully slow robotic drilling is

Private Industry Interest

Planetary Resources -- www.planetaryresources.com

- **“long-term plans include mining asteroids for structural and precious metals”**
- Focus on harvesting water to make fuel and for life-support
- No plans to bring materials back to Earth; for **space-use only**
- 3-ish stage plan:
    1. Survey/analysis of NEOs to determine best targets (2 cubesats launched in 2013 and 2018)
    2. Send probes to targets for close-up surveying, maybe a sample return mission
    3. Mine for water and/or precious metals
- Funded by billionaires (ie google execs) and Luxembourg
- Funding issues, acquired by ConsenSys, no new details :(

Arkyd 6 has mid-wave infrared sensor, second-generation avionics, power systems, communications, and attitude determination and control systems.

Legal Regulations

UN Outer Space Treaty

- Bans nuclearization, limits uses to peaceful purposes, and prohibits claiming sovereignty
- Ratified by 109+ nations
- Doesn't mention companies or mining of materials

US Commercial Space Launch Competitiveness Act of 2015

- grants companies rights to materials they extract from protected space objects
- Some see it as a violation of the sovereignty clause of OST

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Really seems like anything is fair game right now, until someone starts mining regulations will be minimal

Financial Feasibility

- Relevant only to private companies
- Government agencies don't need to make a profit
- ISRU doesn't need to be profitable, just needs to be lower-cost than importing materials from Earth

Need to consider:

1. Research and development costs
2. Exploration and prospecting costs
3. Construction and infrastructure development costs
4. Operational and engineering costs
5. Environmental costs
6. Time cost

Financial Feasibility

Investigated by e.g.: Sonter (1997), **Gertsch and Gertsch (1997)**, Pelech, Roesler, and Saydam (2019), Hein (2018)

GG97 consider a $5B, 12-year mission to mine platinum (~$50k/kg) from an asteroid; find 100% ROI impossible, 50% pretty difficult

Activity:	R&D	Explore	Construction	Launch	Fly	Mine	Fly & Process
Mean Project Year:	2	2	3	6	6	8	10
(Cost)/Sales	($500M)	($800M)	($1,000M)	($500M)	($500M)	($1000M)	($700M)

Activity	Year	Notes
R&D	1 to 5	Develop and test the mining and processing equipment.
Explore Asteroid	1 to 4	Determine mining needs. (For approximately 2 year one way trip.)
Construct Miner & Processing Plant	2 to 5	Start as early as possible, but the final capabilities required will not be known until the exploration mission is complete.
Fly to Asteroid	6 to 7	2 year flight as miner is completed. Includes launch costs.
Mine and Process Asteroid	8	Assume one year for all mining activities. Processing will probably start during mining phase.
Fly & Process	9 to 11	Return to Earth. Continue processing in-flight if required.
Sell Product	11 to 12	Should be accomplished as soon as possible for highest return.

Added issue of tariffs applied to “protect” earth-based mining (or the opposite!)

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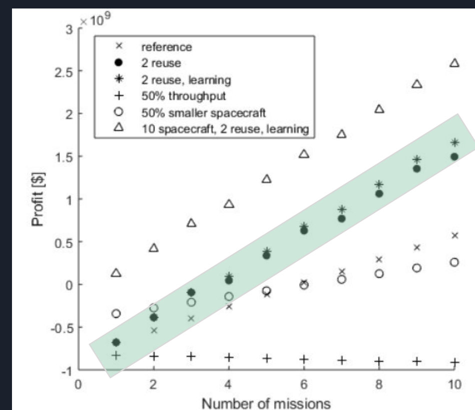
Hein+ explore in-space use of water profitability

- Potential for profit only after multiple missions, with enormous upfront costs (>$50B)
- Not dependent on Earth market, but also not established market for in-space water yet...



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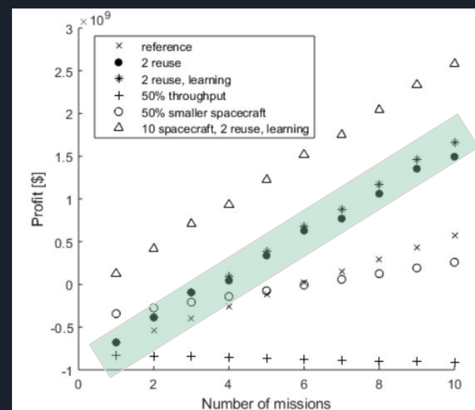
> Mining projects will be incredibly **risky**, have very **long pay-back** periods, and if too much material is returned it will flood the market and **lower the price.**
>
> 1 out of 1 economists polled say "**No way!**"



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Economic Potential (Caveats)

- Even aside from legal disputes
  - Valuation of mineral deposits is iffy
- Economics assumes non-perturbed market structure on Earth
  - Demand for terrestrial applications
  - Prices based on actual/perceived scarcity
  - Only holds in limited contexts (at the beginning, price-inelastic phase)
- Geo-political implications to not relying on rare-Earth mineral deposits in other countries

Yet an ominous feature of the celestial environment seems to threaten the ability of outer space commerce to achieve its potential: celestial anarchy. Although, terrestrially, governments enjoy the sovereignty over their territories needed for the state to define and enforce property rights in those territories, celestially, things are quite different. In outer space, much as in international space, no government has sovereignty. This fact is enshrined in the 1967 Outer Space Treaty, signed by the spacefaring nations. Article II of the treaty prohibits signatory nations from extending territorial jurisdiction to celestial bodies.[2]

The problem celestial anarchy seems to create here is straightforward. Private parties who have property disputes when operating in outer space need to settle their disputes in courts of law. But such courts are within the legal domains of national sovereigns. Enforcing private parties' property rights in outer space therefore requires a de facto concession of national sovereignty, running afoul of Article II.[4] As Pop (2000: 281) puts it, because "the Outer Space

https://www.cato.org/sites/cato.org/files/serials/files/cato-journal/2014/9/cj34n3-8.pdf - Celestial Anarchy: A Threat to Outer Space Commerce?

Economic analyses. All about assumptions.

https://arxiv.org/ftp/arxiv/papers/1810/1810.03836.pdf

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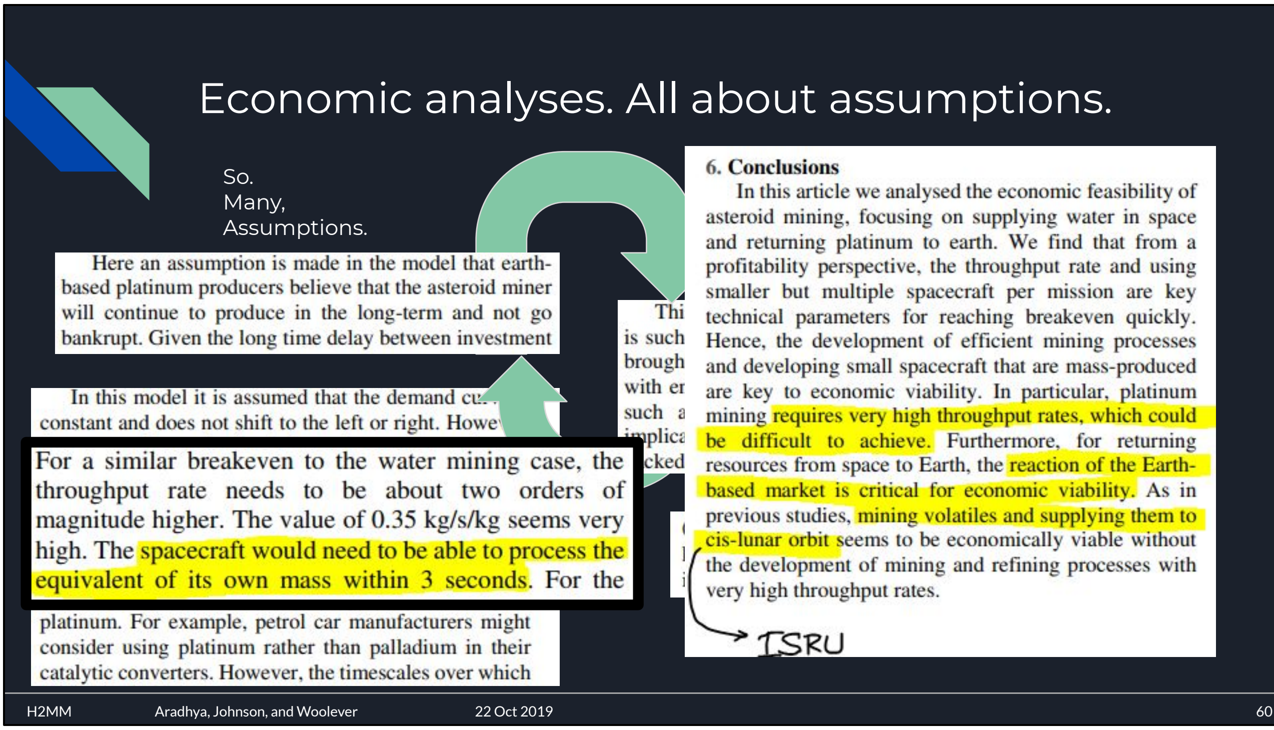
6. Conclusions

In this article we analysed the economic feasibility of asteroid mining, focusing on supplying water in space and returning platinum to earth. We find that from a profitability perspective, the throughput rate and using smaller but multiple spacecraft per mission are key technical parameters for reaching breakeven quickly. Hence, the development of efficient mining processes and developing small spacecraft that are mass-produced are key to economic viability. In particular, platinum mining requires very high throughput rates, which could be difficult to achieve. Furthermore, for returning resources from space to Earth, the reaction of the Earth-based market is critical for economic viability. As in previous studies, mining volatiles and supplying them to cis-lunar orbit seems to be economically viable without the development of mining and refining processes with very high throughput rates.

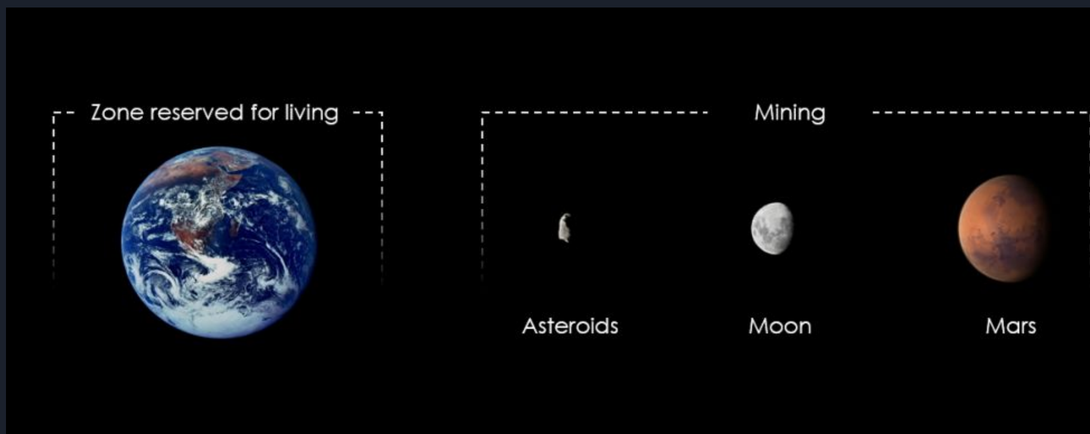
ISRU

https://arxiv.org/ftp/arxiv/papers/1810/1810.03836.pdf



https://arxiv.org/ftp/arxiv/papers/1810/1810.03836.pdf

Socio-cultural-Economic Aspects



https://www.colorado.edu/faculty/zea-luis/sites/default/files/styles/large/public/page/space_biomining_banner_2.png?itok=osg-jj_A

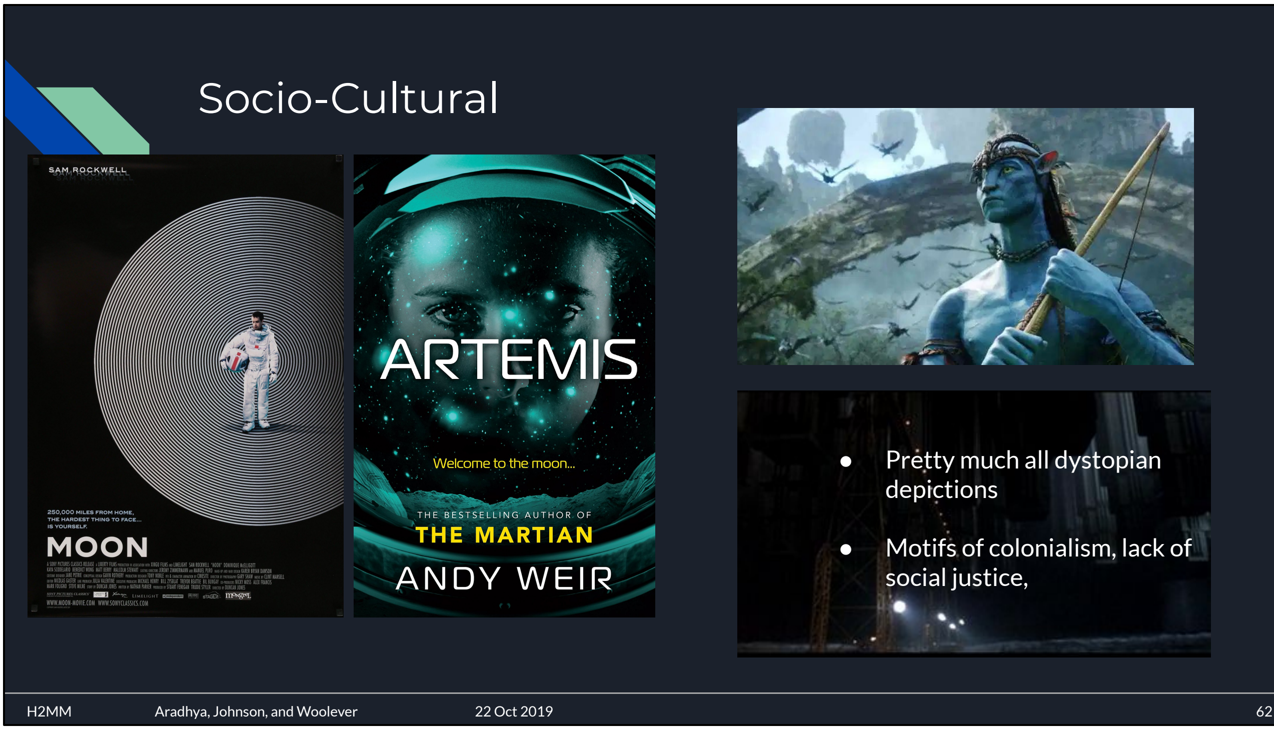


Image sources: Wikipedia, Amazon, https://www.tboake.com/total_recall_discussion.html, https://www.indiewire.com/wp-content/uploads/2017/07/avataraem-xlarge.jpg?w=780

An intensified form of ‘out of sight, out of mind’

Socio-Cultural

Except:
It-IS-simpler-to-train-drillers-to-be-astronauts-than-astronauts-to-be-drillers

- Pretty much all dystopian depictions
- Motifs of colonialism, lack of social justice,

Image sources: Wikipedia, Amazon, https://www.tboake.com/total_recall_discussion.html, https://www.indiewire.com/wp-content/uploads/2017/07/avataraem-xlarge.jpg?w=780

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An intensified form of ‘out of sight, out of mind’

Socio-cultural-economic | Looking up...

- Mining is the only industry that is currently directly applicable in outer space
- Degree of this ‘purity’ may be affected by interactions with mining and capital markets on Earth
- Pre-requisite higher degrees of automation may allow for more egalitarian setups

https://www.inverse.com/article/55060-a-mars-colony-could-be-humanity-s-best-shot-at-a-purely-designed-economy

Oh… re: He-3

Google NGram Search
https://www.reddit.com/r/Futurology/comments/5gi9yh/fusion_is_always_50_years_away_for_a_reason/ - Funding graph
http://blogs.discovermagazine.com/crux/2016/03/23/nuclear-fusion-reactor-research/ - "Why nuclear fusion is always 30 years away"

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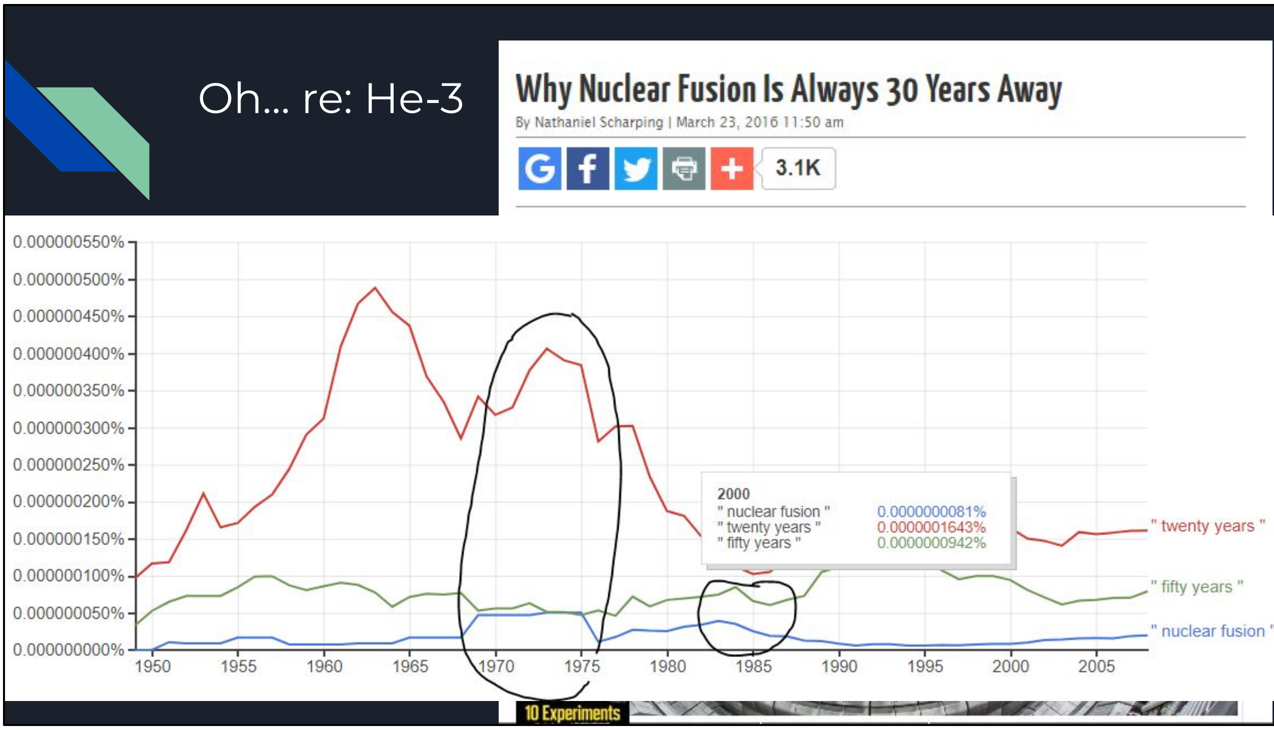

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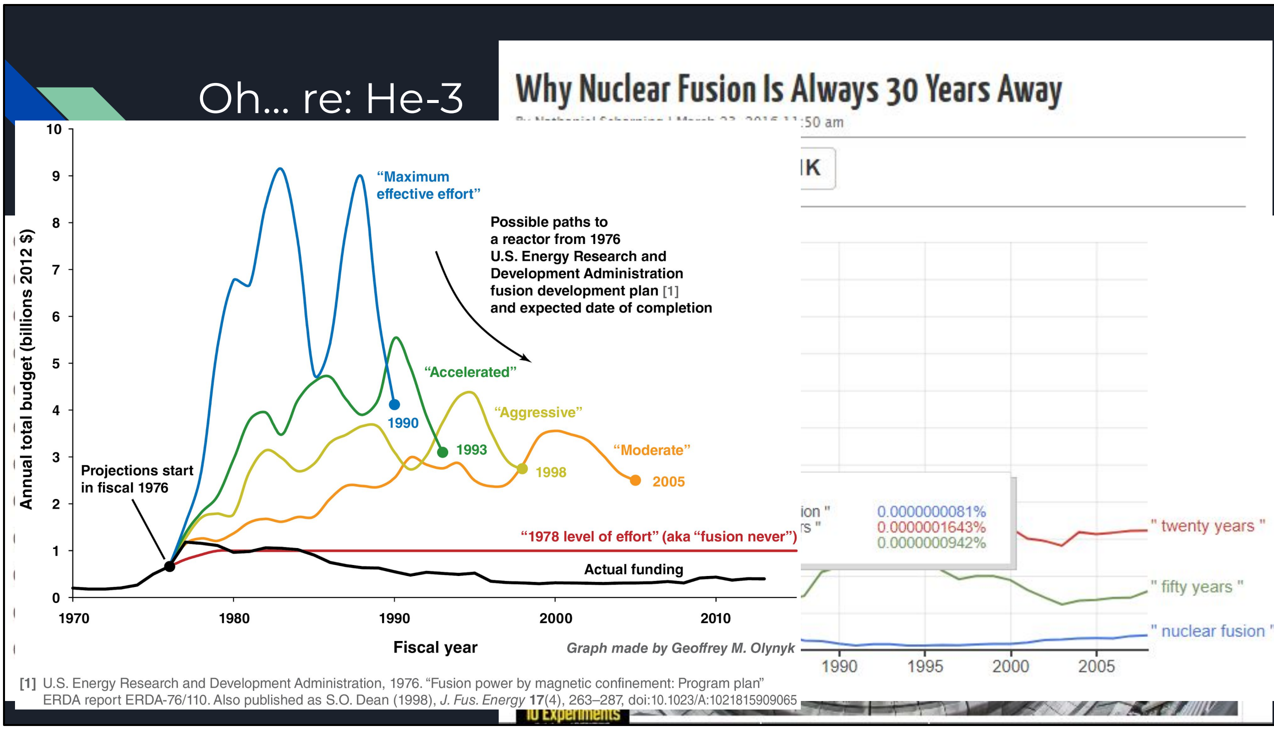

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He-3

- Currently existing uses: ~ fMRI (lung, inhalation, hyperpolarisation)
- Neutron detection : Large absorption cross section, sensitive to neutron spin-polarisation
- Cryogenics

Table 2. The estimation of 3He probable reserves in the lunar regolith.

Category	TiO_2, wt.%	Area S_{TiO2}, km^2	^3He abundance, ppb	Regolith thickness, m	Density kg/m^3	^3He probable reserves, tons	^3He, %,
I	5-10	487114	15.1	4.4	1900	61491	2%
II	3-5	1518587	8	4.8	1900	110796	4%
III	1-3	1586312	5.7	8.1	2000	146480	6%
IV	0-1	34340315	3.1	10.1	2000	2150391	87%
Sum						2469158	100%

- Origin: Solar wind entrained by regolith
- But subsequently lost to vacuum of space

https://www.lpi.usra.edu/meetings/lpsc2007/pdf/2175.pdf
Wikipedia

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Helium is also present as up to 7% of some natural gas sources,[47] and large sources have over 0.5% (above 0.2% makes it viable to extract).[48] The fraction of ^{3}He in helium separated from natural gas in the U.S. was found to range from 70 to 242 parts per billion.[39][49] Hence the US 2002 stockpile of 1 billion normal m^3[48] would have contained about 12 to 43 kilograms of helium-3. According to one expert, about 26 m^3 or almost 5 kg of ^{3}He is available annually for separation from the US natural gas stream.

https://www.lpi.usra.edu/meetings/lpsc2007/pdf/2175.pdf
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Hein+ (2018) https://arxiv.org/pdf/1810.03836.pdf