What Do We Need to Know to Mine Space?

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1. Introduction

Space mining is much in the news of late. The following catchy headlines within the last few years demonstrate this interest "Who wants to be a trillionaire"(Bloomberg Quicktake: Originals, 2019), "Unlimited resources from space – asteroid mining" (Kurzgesagt – In a Nutshell, 2020), "The global race to mine outer space" (Crawford, 2019). We see private companies starting to gear up. So are these next private sector ventures about to make a giant leap into space mining or into bankruptcy. Dahl (forthcoming 2023) considers what we need to know for space mining to become a reality. This paper provides supporting information and documentation for that chapter.

To mine space, we need to know about mining, we need to know about space travel, and we need to be able to imagine and then figure out how to put them together. As Carl Sagan says "Imagination will often carry us to worlds that never were. But without it we go nowhere." So, to go somewhere, I start in section 2, by tracing space mining themes in science fiction. Once we have imagined space mining, I will take a look at the supply chain on Earth. We have variety of prospecting techniques that I will discuss and then speculate a bit on what we know is in Space and how to find more in section 3.

Once we have found our pot of gold, platinum, regolith, or whatever, we will need to get to it and back. In section 4, I will outline what I know about propulsion and rocket science. It will be a short section!

Having gotten to our treasure, we will need to collect the material, pull out the ore, concentrate the ore, and separate out the valuable material from the ore. In section 5, I will consider how we go about these complicated processes on Earth. We expect that to conduct these processes in the harsh space environment will require advanced technology and skilled technicians. In section 6, I will consider the use of robotics in mining and the habitat needs for those technicians that will be needed at the mine. Once we have found the resources, know we can process and return them, but before we send our robots and technicians out to do their magic, we will need to make a final investment decision (FID). This will require that we can expect to profit. Thus, we will need to know our markets. What are the expected costs and benefits at each point in the potential supply chain? To help focus on what we will need to know about markets, I include a spatial competitive equilibrium model in section 7. The model will need a supply equation at each potential supply node, a demand equation at each potential demand node, and the required return to compensate for expected risk. Risk in space mining are likely high. The section ends with a discussion of such risks including a harsh and dangerous environment, finding appropriate resources, unknown technology and cost of mining and transporting of materials in space, unknown evolution of space markets, market structures, and resource prices, uncertainty over the government regulatory policy, and the role for government in space mining

2. Space Mining Themes in Science Fiction

Mining Space has been in the human imagination for more than a century. Serviss published a serial edition, which is likely the first science fiction book that contains space mining. Let's see what his book, *Edison's Conquest of Mars,* tells us about mining space. (Serviss, 1947) In the book, Martian occupiers of Earth had been weakened by disease and fled home. However, light flashes on the red planet suggested the Martians were planning a new invasion. With the help of Edison's inventions of weapons and an electric powered spacecraft, Earthlings had decided to go to Mars and pre-empt the attack.

We must be able to get there. Now humans have demonstrated some capability in this arena to which we will return to later. In the book, a marauding meteor en route disabled one of the ships and killed some of its crew. Landing on the Moon, the dead were buried and the damage ship repaired. Having the Moon as mining or staging area for further incursions into Space is another theme that we will encounter later and a positive externality of mining space may be increases capability to detect and deter asteroids that might pose a threat to Earth.

They found signs of previous life on the Moon and a wealth of large crystalline structures composed of diamonds. Their mining operations consisted of breaking some pieces off to take along, but they did not do any real mining operations on their stop over. But as the diamonds were just lying on the surface, neither spectral analysis or other methods of exploration discussed in a later sections were needed. They noted the diamonds were lying about just waiting for the taking. Thus, the law of capture prevailed but sustainable space mining may require we know how property rights and their enforcement will be handled.

Having left the Moon to proceed to Mars, our Earthlings were caught in the gravity of a comet. They expected to be smashed into the Sun, but were miraculously caught in Earth's gravity and landed back on the Earth. Such gravity assist was first intentionally used to save on fuel and change the inclination of Russia's Luna 3, which circled the Moon in 1969 (Negri and Prado, 2020). With such assist, gravity from a planet or other large space object being orbited can act as a sling shot or a brake depending on the direction of the orbit (NASA, n.d.-a). Numerous subsequent interplanetary flights have used such assist, with the Earth, Venus, the Sun, and other prominent bodies lending their gravitational support.

Setting off again, the Moon was no longer on their trajectory, and they commenced directly towards Mars. This possible change in relative positions between departure point and destination is another challenge that Space mining operations will likely encounter. We will need to know precisely when and where our target mining objects are to determine the best launch windows.

On the way to Mars, Earthlings encountered an asteroid circling Mars, where they had a battle with a Martian mining colony. Although a surprise attack demolished two of the earthling ships, Edison's disintegrator soon won the day for this attack; a subsequent encounter with a landing party from Mars was won as well. More themes arise. On our mining missions into Space, we are hopefully unlikely to have an immediate need to use disintegrators for protection. No sentient life seems to exist on any bodies likely to be within near-term mining range of Earth. The likely nearest-term mining options include the moon and near Earth objects including asteroids (NEAs) and comets (NECs), followed by Mars and its two moons – Phobos and Deimos. Furthermore, the 1967 UN Outer Space Treaty (UNOOSA) (United Nations, 1966) designates that Space should only be used for peaceful purposes. All the countries with space faring capabilities are members of the UNOOSA Committee on the Peaceful Uses of Outer Space (United Nations: Office for Outer Space Affairs, 2022). Hopefully they will all abide by their treaty obligations.

With the exploration of the asteroid, Serviss's Earthlings experimented with the lack of atmosphere and their almost weightless condition. Both of these conditions will have to be contended with, if our mining operations take place on such small objects. We also encountered our first space mining activities. We are not enlightened on how the mining is done, but it doesn't sound too difficult as the asteroid turned out to be made mostly of gold in the form of nuggets. The Earthlings speculated that the Martians must have rationed how much gold they brought back home, so as not to flood the market. You do not want to kill the goose that lays the golden eggs, nor do you want to induce her to lay too many eggs and drive down profits. Thus, what, where, and the structure of the ultimate market will be important inputs into our mining company's decisions. The Earthlings also concluded by evidence at the site that the mining operations had been attacked by pirates. Again, we encounter issues of enforcing property rights.

Given the almost lack of gravity on the asteroid, the Earthlings tried to hurl nuggets by hand back to Earth hoping some would make the trip through Earth's atmosphere without burning up. This seems an unlikely method for returning mined materials to market and we never learn if it was successful or not. We expect not. To land without crashing, we will need power to slow down. The larger the object, the more gravity we will need to overcome and the more power needed to slow down. If the body is large with enough gravity coupled with other needed conditions to hold onto an atmosphere, the atmosphere can provide gravity braking (Universe Today, n.d.). However, heat shields, which will add weight, will likely be required to keep the entry materials from melting or burning up.

Serviss does not provide much guidance on mining, but Isaac Asimov's short story Catch the Rabbit, introduces us to robotic mining of asteroids, which is a likely first step in our space mining adventure (Asimov, 1950). We learn a little about robot mining, which sound rather Earthlike and underground (tunnels, preparing blasts, buttressing the roof, cave-ins). Supposedly the asteroid can be mined robotically without human intervention. However, in this story Asimov's robots seem to malfunction and only continuously mine when humans are present. It seems the technology still needed some work.

A couple of years later, there was a gold rush in progress to mine the asteroid belt for basic building materials and radioactive ores in Heinlein (1952). This again suggests a government role relating to issues in property rights as well as providing needed public services that arise in boomtown atmospheres. Not so likely to be an issue in early space mining endeavors when only a few are likely to get out there and back, but more of an issue as the technology spreads. However, the Stone twins' idea to sell bicycles for prospecting on Mars and asteroids in the book does not seem to have caught on.

Cole and Cox (1964), from the vantage point of science, imagined a world in which humans explored, exploited their minerals, and lived on asteroids. After the successes of the Apollo program, they argued the next step should be exploratory followed by crewed missions to NEAs until more powerful rockets could be developed to take humans to Mars. They sparked the imagination of budding astronauts and scientists. Subsequent robotic missions to asteroids and comets are not so unlike those suggested decades earlier by these two visionary scientists (albonn07, 2009). They provided a timeline and reasons for going to the asteroids, which they called planetoids. Such reasons, still credible today, include information gleaned about the origin or our solar systems, information to identify and deflect any NEAs that pose a threat to Earth, providing resources and staging areas for interplanetary travel and beyond, many are closer than the Moon and other planets making them accessible near-term targets, and they have the potential to be sites for space colonies. They discuss the need for eventually colonization of Space when the limits to growth on Earth might be hit. Asteroids might be returned to Earth orbit for resource exploitation or mined in situ. Hollowed out asteroids might provide habitat for space colonies or converted into ships for space travel (Nicoll, 2014).

Returning to science fiction, in the 1969 movie, Moon Zero Two, the year is 2021. The theme of claim jumping and moon mining laws again reminds us of the need for assignment and enforcement of property rights. A sapphire laden asteroid has been towed and put into lunar orbit, and is to be taken to the lunar surface for mining. This idea does not seem so far-fetched. Although it did not happen in 2021, towing an NEA back to lunar orbit for further scrutiny has been studied by Brophy, Culick, and Friedman (2012). They concluded that the technology existed to tow back a 1000 tonne asteroid (diameter about 7 meters) for about =2.6*271.4/229.6=3.013 billion 2021 dollars with a 10 year mission length. Once in lunar orbit, the asteroid could be used to study and modify mining techniques for space conditions. Since their study, with the entry of the private sector, rockets have improved and cost been reduced suggesting that we could tow back larger asteroids at lower costs than a decade ago.

In Niven (1975) and some of his other novels and short stories, the Sol Belt, the main asteroid belt between Mars and Jupiter, is mined to provide valuable materials for Earth and for colonization of space. In some cases, asteroids hollowed out from mining are used for space habitat. Eventually well-established trading relations are developed between the miners, called Belters, and Earth (Flatlanders). For such trade to develop, players will need to understand market structure and all the trappings of commercial operations are likely needed – accountants, lawyers, and the like with specializations in space trade. Mining tugs, which must help transport resources, are also referred to. Such tugs may even be employed to tow whole asteroids to where they will be processed into saleable material.

Niven (1975p.163) also has some means of propulsion we might aspire to but are only available to the imagination as yet. Buzzard Ramjets use fusion power and run on hydrogen. In them, volatized uranium followed by hydrogen is injected into fusion tubes. The resulting neutrons create fission, which creates heat, which produces fusion, which propels the ship. His imaginary hyperdrives, which allow travel faster than the speed of light, can't be used in our solar system. So, we can postpone more discussion of them until my sequel –mining interstellar space–comes out. Mine our solar system first, the Universe later. These drives do seem to reappear later as warp drive in Star Trek television series and movies and as hyperdrive in Star Wars movies. Leaning towards the science end of science fiction, O'Neill (1977) is the result of a challenge Professor O'Neill presented to his Princeton physics students to design a livable space habitat using technology existing at the time. After brainstorming all of the ideas, the resulting proposal in his article and book is to place habitable space stations at the Earth – Moon Lagrange point L5. L5 is a stable point keeping the station in a constant relative position to the Earth and Moon. Starting with a prototype station, additional modules could be added as they could be developed and were needed Such stations, if successful, would solve the problems of providing energy, materials, and living space, as Earth's population and environmental stress increased.

In the second movie, I have found that includes space mining, Outland (1981), Sean Connery is a marshal on a space satellite for a titanium mining colony on Jupiter's moon –Io. On larger space objects, putting some operations in orbit may be a strategy ultimately used to save the fuel needed to take off from and land on the object or if it's cheaper to provide a livable human habitat in orbit then on the surface. In the movie, miners seem to live on the space station and commute to work on the surface. We learn nothing much about mining in this movie, except that leaving the air lock without our space suit is not a good mining practice. However, Sean Connery in movies is always a hunk, so watching it was not a total exercise in futility.

The fascination with asteroids and mining space continues in both fantasy and fact. In the Asteroid Wars series, Bova (2001, 2002, 2004, 2007), space travelers are fighting over asteroids to mine their riches. Their ships are also propelled by fusion reactors. We have not yet mastered this fuel technology even for terrestrial use. Such imagined reactors highlight the need to dramatically reduce the cost of getting off and back on Earth to make space mining commercially attractive. That is at least until we get space stations in orbit around or on other bodies with mining or processing operations, markets, or transfer hubs (Ghoneim, 2018, 2019)

Space mining themes continue both on and off the screen and in real life. In Cameron's (2009) movie, Avatar, humans are mining a far distant moon. Their operations are threatening an indigenous group and bring us to the theme of corporate social responsibility. These particular miners did not seem so socially responsible. As our early mining targets will not be inhabited before we arrive, such responsibility can be safely put off a future sequel (Lindgreen and Swaen, 2010). While in print, Nicoll (2021) cites 5 recent novels that are sited in asteroid belts.

The one of I find of most interest is *Delta v* (Suarez, 2019). This recent book has the benefit of quite a lot of hind sight. Although most of the sci-fi books related to space mining do not give much detail of the mining process, surrounding institutional arrangements, and health issues, this interesting book set in the near term (2031-2038) has some very compelling descriptions of a range of issues that will face asteroid miners from health issues of space travel, government involvement and international politics, and to technology of the actual mining process itself. Howe (2020) argues that the science in the book is fairly accurate and plausible.

In the book, the rogue mission to mine an asteroid has not obtained the necessary permits to commence their mining operations. After secret training on Earth, the eight chosen for the mission leave from a hotel in LEO. This hotel is used by tourists as well as travel's conducting business in LEO or in transit and sounds like something current space moguls are considering. We experience the high Δv (times the gravity of Earth) accelerating. The target asteroid in the book is the already sampled asteroid Ryugu by Japan's Hayabusa 2 mission. This adds to the factual accuracy in the asteroid's descriptions along with challenges and timing from lift off to Earth return.

3. Prospecting for Mineral Ore and Near Term Targets

As might be expected, prospecting is the search for good prospects worthy of further exploration before development decisions are made. Not so very long ago as measured in geologic time, prospecting was only done up front and personal (the direct approach). We can imagine our prospectors combing prospective areas with their burros in tow. They compared outcrops, seeps, sediment deposits and soil color to those in known existing mineral deposits (Hustrulid, 2021). This first impression was maybe accompanied by some shallow digging to gather further information. However, this earlier direct approach would likely only find deposits, whose existence was signaled on the Earth's surface. Although we still use the direct approach, our visual observations can be made from aerial and even satellite observation.

What we know about mineral resources in Space is limited but is slowly accumulating. As for Galileo, who first perused the heavens by telescope in 1610, one way to learn of these resources is visual observation. However, we have better knowledge and equipment at our disposal than Galileo. Much of what we know about the composition of heavenly bodies comes from using a spectroscope invented in the early 1800's (MIT Spectroscopy, n.d.). By breaking incoming light from space material into its components, scientists in the-know can determine the chemical composition of the objects being observed. In addition, our telescopes are bringing in more light from much further afield. The Hubble telescope was launched into Earth orbit in 1990. This first space telescope, a joint project between the European Space Agency (ESA) and the U. S. National Aeronautics and Space Administration (NASA), not only has a large lens, it is more than 340 miles (547 km) above the Earth, so it avoids more of the distortions from the atmosphere than Earth bound telescopes. With periodic repairs, the most recent conducted in mid 2021, it is still returning images to Earth (Garner, 2018; Wild, 2021). The recently launched James Webb, even further away from Earth (~1.5 million miles (2.4 km) with a larger mirror and more capability with infrared wavelengths will not only help us look further out and further back in time, it will also provide more information on the mineral composition of bodies in our solar system (Goddard Space Flight Center, 2022)Not only can we see further, faster and deeper, but science has come to dominate how we look for and interpret what we see and the data we gather. The field of Geology, or the study of the Earth's properties and its evolution, came into being as a discipline in the latter part of the

1700's (Bressan, 2016). These properties coupled with direct observation and an understanding of regional geology may help determine the likely extent of deposits.

Science has delivered some indirect methods to determine mineral deposits. Geophysics, which includes the study of Earth's structure and how this structure evolves, and geochemistry, which includes study of the chemical composition and chemical interaction of the Earth's minerals are two such disciplines. Geophysicists may use Earth and mineral properties to signal the presence of deposits.Magnetometers, often from the air or on a ship, detect differences in magnetic intensity and may signal mineral deposits more than 100 meters below the surface. Differences in gravity are detected by gravity meters signaling the density of the material beneath the surface (Wet, 2011).

There are a variety of electrical and electromagnetic methods for surveying mineral possibilities with more variants than for other methods (Wet, 2011). Purely electrical methods rely on measuring the conductivity and resistivity of materials. In the simplest case, an electric current passes between two initial surface electrodes, the current passes underground through the material of interest, and it passes through two terminal electrodes. Measuring the strength of the current when introduced and at the terminal points indicated possible composition of material between them. For example, large sulfides mineral deposits, which are good candidates for valuable mineral ores, are highly conductive. The current may be natural underground currents such as those that exist between some materials or those induced by electromagnetic waves from the atmosphere and beyond. Alternatively, the current may be artificially induced using DC current or very low frequency electromagnetic waves that will not generate a significant magnetic field around them. One of the variants of these methods include how many terminal electrodes are used and their placement (links to a variety of electrical resistivity methods can be found in (Sean, 2019).

n electromagnetic survey methods, typically an AC current is set up in a coil on or above the Earth's surface. The coils may vary from 1 meter to a km in diameter. This current sets up a magnetic field around it with alternating north – south poles as the current changes direction (EPA, 2016a) and emits electromagnetic radiation. The magnetic field sends back signals to the above ground receiver. Measuring the magnetic field intensity from these return signals at various depths provides information about the conductivity and composition of underground materials (Alaska Division of Geological & Geophysical Surveys, n.d.). Two basic methods are employed. Circular coils emit sinusoidal electromagnetic radiation. The frequency chosen determines the depth of the returned signals with lower frequencies returning information from greater depths. An alternate configuration is a square usually single loop of wire in which the current passed through is a constant in one direction, is shut off, and then is constant in the other direction, then shut off, until the next cycle begins. The radiation in this case is emitted in what are called rectangular waves. The longer the side of the square the deeper will be the return signal from. The shutting off of the current causes a voltage drop in the receiver. This voltage drop measured at successive periods of time brings back readings from lower depths providing information and electric conductivity of the underground with clues to its composition (EPA, 2016b).

Seismic methods are heavily relied on in prospecting for hydrocarbons and at times are used in the mineral industries. Seismic waves are mechanical waves that travel through the Earth and are caused by pressure pulses that are transmitted by particles bumping into one another. They are conducted from land, sea, and air. In a seismic survey, the waves are typically induced on the Earth's surface by vibrators that thump the ground or by air guns if the survey is being conducted from the ocean. When the waves hit boundaries of different layers of material underground, the waves get reflected and refracted back to the surface where a number of receivers measure the characteristics of the returning waves. These receivers are called geophones on the Earth's surface and hydrophones on the ocean surface. The velocity and strength of the return signal to the various receivers are analyzed to deduce the characteristics of the materials below the surface (Utah Geological Survey, 2017). Seismic surveys have gone as deep as 150 km but for prospecting they would typically be much shallower with hydrocarbon surveys up to around

10 km deep (Talwani and Kessinger, 2003). For space objects with no atmosphere and no surface water, seismic surveys will only be done from the solid surface of the objects.

Radiometric techniques collect information on radioactive emissions. These emissions include alpha particles (two protons and two neutrons bound together), beta particles (fast moving electrons), and gamma rays (very high energy and low wave length electromagnetic radiation). Equipment used for these measurements include Geiger counters, with relatively short range and an inability to distinguish between types of radiation and crystal scintillator that have a longer range and detect gamma rays. Such radiation passing through a gas has enough energy to knock off electrons and create ions. The earliest equipment designed to detect alpha particles was the Geiger counter developed in the early 1900s (Shampo, Kyle, and Steensma, 2011). It only measured alpha particles. Later improvements culminating in the Geiger Müller counter in 1928 also measured other types of radiation including beta particles and gamma rays. In this counter, a metal tube had a wire going down its center. A voltage difference was created between the wire and the tube wall almost high enough to cause a spark. When the radiation entered the tube, which was filled with a mixture of argon (an inert gas) and methane (a non-inert gas), it knocked electrons off of the argon molecule creating negative ions (Rutherford, 1911). When a negative ion got to the positive electrode, it caused a pulse of current to flow, which a counter counted. The counter does not measure the strength of the radiation or distinguish between the types of radiation but rather it counts the number of ions created by radiation entering the gas filled tube (U.S. Nuclear Regulatory Commission, 2020). The non-inert gas is called the quenching gas. It absorbs the positive argon ions so they do not neutralize the negative ions and prevent a current pulse (Pass My Exams, 2020). After each count, the tube must reset to remove to await the arrival of new particles. Such counters are used today and the inert gases in the tube are typically argon, helium, or neon and the non-inert gas is a halogen such as bromine or chlorine (Siegel and Eskandari, n.d.). As we are all surrounded by radiation, the counting needs to be calibrated for the level of background radiation.

There are two basic types of tubes in Geiger counters. Ones with very thin windows, often of mica, let in alpha and beta particles. Heavy alpha particles only travel about (1-3 cm) through the air, very light beta particles travel around three meters. They travel even shorter distances in argon, wood, rock, and metal. Thin window varieties are most efficient for counting beta particles as many alpha particles will not make it to the counter. Whereas high energy gamma rays are likely to pass on through. How far gamma rays penetrate depends on their energy level. Some very high level gamma rays may travel around a km through air before losing 90% of their energy. However, the gamma rays from minerals of interest have lower energy levels and are likely to travel less than half as far in air (Radioactivity, n.d.; Thorondor, 2020). With the windowless version of the Geiger counter, the gamma rays penetrate through the tube wall, while the alpha and beta particles do not (Connor, 2019). Nevertheless, many of the gamma rays are able to pass on through without being counted. For a good lecture on Geiger counters see ADM Nuclear Technologies (2021)

The USGS started using a car mounted Geiger counter to search for uranium starting in 1945. It could detect large deposits while driving around 48 km/h (30 mph) at distances of up to about 122 meters (400 ft) (Nelson, 1953). More sophisticated versions of the Geiger counter are still in use (Siegel and Eskandari, n.d.), but they are only used for surface deposits and are most efficient at detecting beta particles (Haldar, 2018). They can, however, give us information from much deeper by measuring radiation from core samples that have been brought to the surface. For longer range measurements that better measure gamma rays have been developed.

Such radiometric techniques may help find commercial deposits of thorium, potassium, uranium, and other elements that have radioactive isotopes that emit gamma rays (Geoscience Australia, n.d.). They may also be a signal for nonradioactive accompanying minerals such as titanium and zircon (Siegel and Eskandari, n.d.). Currently the favored technique to detect gamma rays for mineral prospecting is to use crystal scintillation with favored crystals including sodium iodide (NaI) doped with thallium. The operational principles of scintillators are as follows. Gamma rays originate in the nucleus of the radioactive isotope. Different isotopes of an element have the same number of protons but differ in the number of neutrons. When the gamma ray encounters other atoms and molecules, it may pass on by or it may interact with their electrons and be absorbed by one of their electrons increasing the electron's energy and knocking it free (photo-absorption) or it may be scattered off of the electron with the gamma ray losing energy and the electron gaining some (Crompton effect). If the gamma ray is at a very high level a third effect may occur called paired production. When it strikes an atom, it may produce a positron and an electron. When the pair comes together it produces a pair of lower level gamma rays. These in turn may create the other two effects.

Although using all these effects to measure gamma rays is rather more complicated than the Geiger counter, a part of the measurement involves using the photo absorption effect. Thus, when the gamma ray creates a photo-absorption effect, the effect is magnified by a photo magnifier tube. The crystal in this tube creates a scintillation or pulse of light that is turned into a pulse of electricity that can then be measured as in the Geiger counter . Scintillators can measure radiation at greater distances, at lower levels of radiation, and also determine the energy level of the gamma rays. They may be portable hand held models, airborne models and even down hole models (Vaughn, Rhoden, Wilson, and Paul, 1959).

We can also extend our investigation deeper by taking core samples and using laboratory analysis to determine core composition. The first modern core drilling used diamond bits developed in the 1860s (Konya, 2020). The deepest hole ever dug to take a core sample is the Kola Superdeep Borehole on the Russian Kola Peninsula with diameter of about 22.9 cm (9 inches) and a depth of 12,262 meters (40,230 feet) (Ault, 2015). So we are now able to look deeper than we can commercially mine.

Some techniques rely on artificial bombardment of such samples with radiation. For example, neutron bombardment can be applied to determining concentrations of various elements including aluminum (Al), potassium (K) and REEs (REE) (Dentith and Mudge, 2014) (IAEA, 1999). Advantages of using neutrons include lack of a charge, which allows them to penetrate more deeply than charged particles and their bombardment is not destructive allowing analysis and re-analysis over time for different properties (Dove, 2015). Artificial bombardment with alpha and beta particles as well as gamma and X-rays and ions conducted as well. The study of nuclear geophysics deals with these radioactive techniques (Dentith and Mudge, 2014).

Meteorites provided our earlies samples from Space objects but we also have very small samples from actual visits to the Moon and some asteroids. Since 1985, more than 5 missions from four space agencies (U.S. – NASA, European Union (E.U. – ESA, Japan – JAXA, China – CNSA) have made it to asteroids and have included flybys, orbiting, landing and returning samples (NASA, 2021b).The two most recent asteroid orbiting probes were to land and take samples and return them to Earth (U. S. Osiris-Rex and Japan's Hayabusa-2) (NASA, 2021b; Williams, 2022). Hayabusa II successfully returned a sample to Earth in December, 2020 (Rincon, 2020). Osirus-Rex landed and took samples in October of 2020 and is scheduled to return to Earth in 2023 (Garner, 2021).

The last prospecting method I will touch upon is geochemistry, which is based on identifying materials based on their chemical properties. Typically surveys are conducted and samples are taken and analyzed. Survey design requires knowledge of the mobility and dispersion of the minerals. It includes analysis of the physical and chemical properties of the minerals themselves, oxidation, the related geology, vegetation, weather, the physical features of the area of interest along with relevant interactions. Most commonly concentrations of economically important materials or marker materials are sought out. Orientation surveys often take samples of rock, soil, sediment, water, biological makers, and gas. Enough samples need to be taken to indicate the extent and homogeneity of potential ore bodies (Jaacks, Closs, and Coope, 2011).

Once the sample material is collected, the material is analyzed for its composition by various methods. Colorimetric analytical techniques are straightforward and were being used starting in the 1950s. In them a sample is treated and the color of the treated material indicates the presence of particular chemicals. For example, the treatment may be a reagent added to the sample as the early use of dithizone for zinc and lead; Shining an ultraviolet light can identify the presence of fluorescents with common fluorescing minerals including calcite and fluorite (The Fluorescent Mineral Society, n.d.; Webb and Thompson, 1977).

Later techniques include atomic absorption spectrometry (AAS), inductively coupled plasma mass spectrometry (ICP_MS) mass spectrometry, X-ray fluorescence (XRF), instrumental neutron activation analysis, discussed above (INAA), digestion methods to decompose material, and chemical information from biological sources (Jaacks et al., 2011).

AAS certainly has space applications as earlier versions of spectrometry had already been used to determine the presence of different metals in the Sun and stars. AAS had its first geochemical applications in the 1960s and is fairly easy to set up (Hartman and Mutmansky, 2002; Viets and O'Leary, 1992). The basic principle underlying AAS is that the atoms of different elements have their own characteristic wavelengths and will only absorb those wave lengths. The material to be analyzed is put in solution and atomized or broken into its atoms, often with a flame but other methods can be used. A light source creates the wave length of the element to be tested for. When the radiant light energy hits the sample, the atoms being tested for absorb radiant energy and excite electrons to a higher energy level. The emissions from the excited atoms are unique for each atom and produce a spectrum that consists of the frequencies of the emitted radiation. By comparing the spectrum to know spectrums, we can identify if the targeted element is in the sample. Darker lines in the spectrum indicate wavelength that have been absorbed. The higher the concentration, the darker the spectrum line (Scheeline and Spudich, 2022; Visser, 2021).

The next three techniques (ICP-MS, XRF, INAA) are more complicated and require skilled technicians coupled with computer analysis of the results. ICP-MS can very precisely measure most elements. In it a plasma is induced by an electromagnetic coil in argon. Where a plasma is matter at a temperature so high that electrons separate from the gaseous atoms into an ionized gas. This is the ICP part of the acronym. The sample is typically dissolved in water or treated with acid to become a liquid that is then atomized and then ionized by the ICP. These ions are measured by a mass spectrometer to determine the elements in the sample (Agilent, n.d.; Plasma Science and Fusion Center, n.d.). This technique is much faster than AAS because it does not require a different emission light source for each element tested and with increased discrimination it is able to test a wider range of elements. Other versions of this technology use other measuring methods such as ICP_OES, which measures optical or light emissions instead of the mass of the ions (Anderson, Dunne, and Uhrie, 2014)ICP-MS is an elemental analysis technique, meaning it is used to measure elements, rather than the molecules and compounds that are measured by LC/MS and GC/MS look for LC/MS and GC/MS How does a mass spectrometer work.XRF analyzers for industry use were first available commercially in 1955. They use gamma rays from radioisotopes or excitation tubes to bombard solid samples with gamma rays. The resulting X-ray spectrums created can be analyzed to determine some the specific elements included in the sample. Portable XRF devices can be used in the field but only measure to a depth of 3 mm (Jaacks et al., 2011).

Samples may be treated before analysis to remove gangue to get a more concentrated ore that will improve accuracy in measuring the concentrations of the desired material. This processing is often done by treating the ore with a hot acid solution (Jaacks et al., 2011). Their figure 3.4-3 shows various solutions of reactants that will dissolve out minerals and metals of various ores. For example, distilled water may be used for soluble minerals, whereas weak acid solutions may be strong enough to dissolve carbonates, while stronger concentrate of nitric and hydrochloric acid (agua regia) might be needed to dissolve out minerals in silicates.

Biological methods might also be used to identify potential mineral deposits. In some cases, certain plants are attracted to certain minerals (e.g. buckwheat may be indicative of gold (Rare Gold Nuggets, 2017). Ahmad, Khan, Page, Alamri, and Hashem (2021) investigate what plants may signal coal, marble, and chromite deposits. Some examples of their find include Arabic gum trees signaling chromite, fig trees signaling marble, and olive trees signaling coal. In addition, since plants absorb minerals through their roots, investigating the minerals in the roots, branches and leaves in plants may provide evidence of the mineral potential below (U.S. Department Of The Interior Geological Survey, n.d.). As we have not identified life on any likely first mining targets such biological methods are not so likely to have space mining applications at least near term.

Hartman and Mutmansky (2002) show a number of applications for various geochemical methods. The above discussion is certainly not an exhaustive consideration of all the geochemical composition but rather some of the basics. All methods evolve over time with modifications that make them better (i.e. faster, cheaper, more accurate, etc.). In considering the above techniques, some may involve multiple processes. (e.g. Some of the radiometric techniques involve geochemical changes). Often a single prospecting method does not provide conclusive information on what is underground, and more than one technique used to reduce ambiguity. For more on these and other geophysical methods and their applications see Wet (2011) and Dentith and Mudge (2014).

Although the above methods have been discussed in the context of prospecting for minerals, many may be used at other points in the supply chain where we need to know the concentrations of valuable minerals in our ore. Many of these methods have been or will be applicable to prospecting in Space. We will learn more about these applications in section 5.

Not only the composition of space bodies, but also their location will also be an important determinant of cost and whether they are near term targets. The moon, our nearest celestial neighbor, though technically not an asteroid (too big and it doesn't orbit the sun), may have some possibility for mining. It is thought to contain large amounts of titanium (an important alloy for spacecraft but abundant on Earth), Helium 3 (that might power fusion reactors), water (that could be used for rocket fuel, life support and radiation shielding) and rare earth minerals (David, 2015; Space.com, 2011). See Jet Propulsion Laboratory (2015) for a brief discussion of how moon mining might work. As the moon has been hit by numerous meteorites, it may have abundant other minerals as well. For more on the moons chemical composition from lunar samples taken on the eight Apollo and Luna lunar missions, see Permanent (2022).

Targeting the Moon for mining has already begun. Moon Express founded in 2010 has a stated goal of mining the Moon (Foust, 2018b; Moon Express, n. d.). In 2016, it was the first commercial company to receive U.S. government permission to travel out of Earth's orbit. However, the company missed the target of winning Google's Lunar XPRIZE in 2017, as did all the other entrants. When a major investor pulled out in 2017, they struggled until receiving a NASA contract in 2018. They then focused their attention on landers that could take about 450 pounds to the moon (Carrazana, 2018; Ioannou, 2017; Jet Propulsion Laboratory, 2015). The status of Moon Express is not clear after it lost a court case to Intuitive Machines, LLC in 2018 and had to pay in cash and equities (Werner and Foust, 2018).

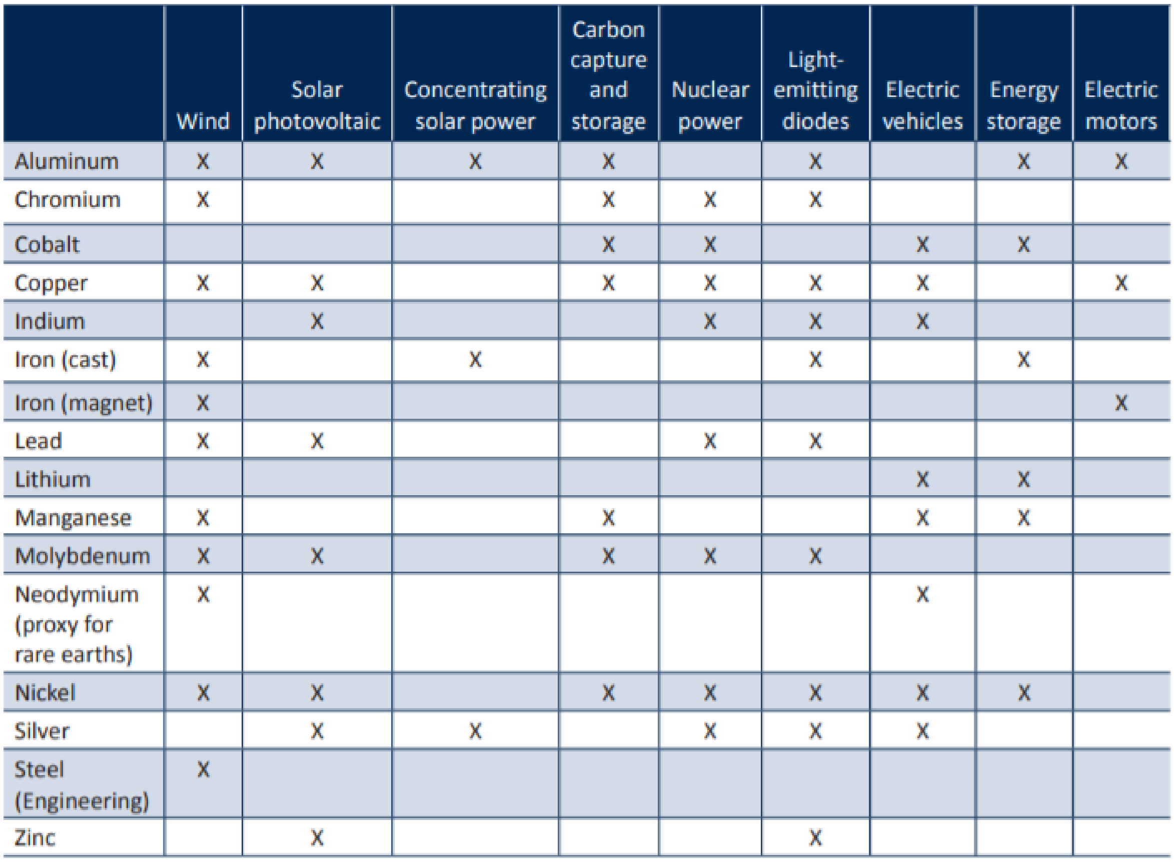
NEAs are also clearly a near term target. The two most prominent companies originally targeting asteroid mining were Planetary Resources, which announced its intensions to mine asteroids in 2012, and Deep Space Industries, which announced its intensions in 2013. Planetary Resources strategy to bring down costs would be to use water and resources in space to avoid having to port all materials from Earth. Their first focus was to be on water and ice, which would be converted to fuel and sold as rocket propellant. They made their first successful Earth satellite demonstration launch from the International Space Station in 2015 and a second demonstration launch of an Earth satellite with technology to detect water on nearby celestial bodies in 2018 (Wikipedia, ~2020) (Lewicki, 2018). As NASA switched their focus from asteroids to moon exploration and mineral prices tanked, Planetary Resources switched their focus to Earth observation (Boyle, 2019). Suffering from funding issues, they were acquired by ConsenSys, Inc., a block chain company, in late 2018 (Foust, 2018a). Although their future within ConsenSys is uncertain, the acquisition was accompanied by vague pronouncements of democratizing and decentralizing private-ordering and commerce in space.

Deep Space Industries was also first focusing on water, but in their case it was on a water propulsion system to reduce the cost of asteroid mining. In 2016, they announced plans to visit a near Earth asteroid by 2020 (Boyle, 2016, 2019). However, as the times changed, they too needed to switch their focus away from asteroid mining to endeavors closer to Earth. They turned to their water propulsion system, called Comet, which is now being used by four small satellites. This system uses electricity to heat water to steam and create propulsion. In early 2019, they were acquired by Bradford Space, which manufactures satellite control systems and will continue to support the comet propulsion technology (Boyle, 2019).

A number of startups that are targeting space mining seem to still be in the game. AstroForge was founded in California in 2022 with a target of refining PGMs in Space on a small scale and bringing them back to Earth by the end of the decade (Young, 2022). Asteroid Mining Corporation, Ltd (AMC) founded in 2016 in Liverpool is also targeting off-world mining for Earth return. They have been working on satellites and robotics to make that happen, starting with telescopic scans from LEO in 2025 of near Earth and main belt asteroids. Scans will be followed by probes to visit promising targets with a goal of eventually processing and returning 20 tonnes of PGMs to Earth (Asteroid Mining Company, 2022). Ispace founded in Japan in 2013 (Ispace, 2021)and Offworld founded in California in 2016 are both targeting robotics for use in space mining among other things (Crunchbase, 2022b; Offworld, 2021). Kleos Space founded in Luxembourg in 2017 (Crunchbase, 2022a) and OrbAstro, a UK and New Zealand based company, founded in 2018, are both targeting small satellite information services that can help prospect asteroids and other space bodies (Berger, 2021; Kulu, 2022; OrbAstro, 2022)

Although these asteroid mining pioneers have put us closer to asteroids, some of the developments suggest that space mining is not as close as they had hoped. However, technical change and the move toward green energy applications could dramatically increase the demand for certain metals. For example, gallium (#31), germanium (#32), selenium (#34), indium (#49), and tellurium (#52) are used in electronic and solar energy application; cobalt (#27), hafnium (#72), and rhenium (#75) are used in alloys that can withstand high temperatures with applications in aerospace, military, and medical industries; the REEs praseodymium (#59), neodymium (#60), terbium (#65), dysprosium (#66), and lutetium (#71) have uses in wind turbines, efficient lighting, electric vehicles, digital equipment and in medical devices, and lithium (#3) is important for batteries where light weight is important (Angelo, n.d.; Exter, Bosch, Schipper, Sprecher, and Kleijn, 2018; Haque, Hughes, Lim, and Vernon, 2014; Timperley, 2018). Thus understanding how these technologies evolve will be important inputs into decisions to undertake space mining operations. Arrobas, Hund, Mccormick, Ningthoujam, and Drexhage (2017) summarize the uses for some of these metals in table 1.

Table 1 Important Metals for Low Carbon Uses



	Wind	Solar photovoltaic	Concentrating solar power	Carbon capture and storage	Nuclear power	Light-emitting diodes	Electric vehicles	Energy storage	Electric motors
Aluminum	X	X	X	X		X		X	X
Chromium	X			X	X	X			
Cobalt				X	X		X	X	
Copper	X	X		X	X	X	X		X
Indium		X			X	X	X		
Iron (cast)	X		X			X		X	
Iron (magnet)	X								X
Lead	X	X			X	X			
Lithium							X	X	
Manganese	X			X			X	X	
Molybdenum	X	X		X	X	X			
Neodymium (proxy for rare earths)	X						X		
Nickel	X	X		X	X	X	X	X	
Silver		X	X		X	X	X		
Steel (Engineering)	X								
Zinc		X				X			

Source: Arrobas et al. (2017)

When earthly material sources become too sparse or space activities resource needs loom large, space mining many regain its luster. As with any green field mining venture, mining asteroids or other space objects mining will require prospecting to find the commercial grade possibilities. Such discovery will eventually require orbiting, landing, and sampling. To pick our prospects for further investigation, we can first turn to the mounting information on where the near Earth asteroids are, what is their composition and their orbits. In 1997, a near Earth asteroid (1997 XF11) almost a kilometer in diameter was discovered that might potentially hit the Earth in 2028. Although this asteroid was later found to be non-threatening, the scare led to the founding of the NASA's Center for Near-Earth Object Studies in 1998. Since then they have found more than 18,000 near Earth objects greater than 1 km in diameter with orbits that come within 195 million km of the sun and 50 million km of the Earth (Jet Propulsion Laboratory, 2018). The majority of these near Earth objects (NEOs) are asteroids or rocky debris from the beginning of the solar system and a small percent are comets, which are made of ice, gas, and dust that can melt when the sun shines on them (hence the tail) (Jet Propulsion Laboratory, n.d.-a).

NEOs proximity to Earth make them likely candidates to begin a space mining venture after the moon or perhaps even before, as many are easier to access than the moon. These asteroids are also being watched to indicate whether they are potentially harmful object (PHAs). Such is the case if they are on a near collision course with Earth and considered large enough to cause significant damage from such a collision (For more precise definitions of PHAs see CNEOS (n.d.); (Swinburne University of Technology, n.d.).

From near Earth objects, Kargel (1994) considers metalliferous asteroids as promising candidates for asteroid mining, surveys work on the metal content of these asteroids, and cites the value for some of these asteroids if the precious metals could be brought back to Earth. Wasson (1974) suggests that about 5% of meteorites have been in this category.

The most numerous asteroids within our solar system are in a belt further out between Mars and Jupiter. They are called the main belt asteroid (MBA). Although even more technically and economically challenging to mine, they are immensely plentiful with more than a million specimens with diameters greater than one kilometer (Laboratory, n.d.). They are unlikely to be our first mining targets with the Moon and near Earth objects being more accessible. However, were we to colonize space, particularly Mars, these mineral sources become much more appealing.

Even more massive but less known is the Kuiper belt of objects (KBOs) beyond Uranus (orbiting the sun at more than 30 Au or 30 times the distance from Earth to the Sun). It contains Pluto (Erickson, 2022). Demoted to dwarf planet status, Pluto has more happily gained some sibling dwarf planets (Ceres, Haumea, Makemake, and Eris) (Tillman, 2019). Surface study of objects in the Kuiper Belt suggest they consist mostly of frozen volatiles including methane, ammonia, nitrogen, and water in varying degrees. Larger objects are more likely to be able to keep hold of more of the most volatile compounds, while smaller ones may have surfaces that contain more water ice (Brown, 2012a, 2012b). So the amount of minerals and water in asteroids is pretty amazing and the information about them is slowly and steadily mounting.

NASA's New Horizon Space probe launched in 2006 reached its closest approach to Pluto in 2016 with equipment to measure atmospheric composition, color mapping of the surface, atmospheric emissions, solar winds around Pluto, and its moons (The Johns Hopkins University Applied Physics Laboratory, n.d.). New Horizon sent back information on an even more distance KBO (Ultima Thule) (https://solarsystem.nasa.gov/news/807/new-horizons-successfully-explores-ultima-thule/; (Laboratory, 2019) http://pluto.jhuapl.edu/Ultima/Ultima-Thule.php; http://pluto.jhuapl.edu/. You can link to an animated gif file with the movements of these asteroid belts along with planetary motion at The International Astronomical Union (n.d.). So the technology exists to get us to the furthest asteroid belt to have a look. We can even get beyond as NASA's Voyager I and II launched in 1977 left the solar system into interstellar space in 2012 and 2019, respectively. However, New Horizon with a payload of about 30 km, a price tag of $800 million, and a 13 year one way trip to Ultima Thule 13 years, suggests we will not be mining this asteroid just yet.

4. Propulsion and Rocket Science

With prospecting tools and likely targets, the next challenge is how to get to these places starting with the biggest challenge – escaping Earth's gravity. Although Serviss's Edison used electricity for all his Space energy needs, rocket ships to date have used chemical combustion rather than electricity to escape Earth's gravity. Fuels include RP-1 (Space grade kerosene) coupled with liquid oxygen (LOX) for take off. This combo was used in the Saturn V, which launched crewed missions to the Moon and the SkyLab space station. More recently, SpaceX has used the RP-1 and LOX combo to launch their Falcon 9 starting in 2010 and their Falcon Heavy starting in 2019 (SpaceX, 2022). After lift off, Saturn V's higher stages were fueled with liquid hydrogen (LH2) coupled with LOX. (National Air and Space Museum, n.d.-b). Solid rocket fuels (aluminum and ammonium perchlorate) coupled with LOX have replaced RP-1 and LOX in some instances as in the first stages of U. S. Space Shuttle launches (1981-2011) (NASA, 2005). SpaceX has been testing its new reusable Starship with an orbital launch expected in July of 2022. It is the first to use a combination of liquid methane (LCH4) and LOX as a launch fuel for both its stages (https://www.cnbc.com/2022/06/14/elon-musk-spacex-starship-ready-to-fly-by-july.html). This fuel combo is called methalox. (https://www.nasaspaceflight.com/2022/03/methalox-race-to-orbit/)

The RP-1/LOX combo (called kerolox) has the advantage of being relatively cheap and dense. However, it leaves a residue when burned, which is a problem for reusable rockets. The LH2/LOX combo, called hydrolox, is clean and the most efficient fuel combo, but hydrogen has a very low density and boiling point. Thus, it takes more energy to liquify and store the hydrogen. In addition, hydrogen's boiling point is much lower than for oxygen posing some thermal difficulties in keeping them both liquified in a shared tank area. Methalox is clean, relatively cheap, has a density more similar to kerosene with an efficiency closer to hydrogen. Further, possibilities exist for in situ generation of methane for Space refueling using hydrogen and carbon dioxide to produce water and methane. Earlier issues of combustion instability for methalox seem resolvable with newer rocket technology. The most active launch companies are pursuing methalox fuel technology and it seems to be the likely new standard for the upcoming reusable launch rockets (https://www.nasaspaceflight.com/2022/03/methalox-race-to-orbit/).

With long term storage an issue for liquid hydrogen, historically hydrazine related compounds based on ammonia have been turned to for fueling intercontinental ballistic missiles and to sometimes provide energy for takeoff and maneuverability on longer term Space missions, where solar is not feasible. (Fletcher-Wood, 2016). However hydrazine is being phased out as a launch fuel as it is quite toxic, with greener alternatives to hydrazine products being sought afterby NASA and the European Space Agency (ESA) (European Space Agency, 2001; Mohon, 2021). While hydrazine is still used as a launch fuel by some Chinese and Russian launches (Berger, 2020; PBS, 2013). Examples of hydrazine used for take-off and in flight electricity generation include the U.S. Space Shuttle (NASA, n.d.-c), the U. S. Mars Curiosity and Perseverance Rovers, launched 2011 and 2020 (NASA, 2020b, 2022c), the UAE Hope mission launched to Mars in 2020 (Rehm and Bartels, 2021), and the James Webb Space Telescope launched in 2021(NASA, n.d.-d).

The universal popularity of chemical fuels results from their high thrust despite their high weight disadvantage. Such propellant typically account for 85% or more of take off weight leaving only 15% or less for the rocket and payload. (Petit, 2012). The largest payloads sent into Space include some of the Apollo missions with payloads to the Moon around 50 tonnes propelled into Space by Saturn V rockets. NASA's Space Launch System (SLS) and SpaceX's Starship Super Heavy are hoping to beat that payload record (Michaux, 2021). Although 50 tonnes seems like a lot, by conventional Earthly mining standards, it is quite small. It is the approximate weight of a Boeing 747 at takeoff. However, annual Earthly production of iron exceeds 1 billion tonnes and of nickel exceeds 2 million tonnes (Dahl, Gilbert, and Lange, 2020). Trains with wagons of 105 tonnes of cargo up to 226 wagons long haul iron ore in Australia (Railway Technology, 2001).

Edison's fictitious rocket avoided the heavy weight of burnable propellant by was using electricity and Serviss (1947) indicated that Edison "had mastered the problem of how to produce [electricity], in a limited space." Unfortunately, Serviss does not enlighten us on how his fictitious Edison did it. We do use electricity in rockets but not for lift off from Earth as the existing technologies do not provide enough thrust.

Propellant is by far the largest need for energy, but it is not the only critical energy source. Electricity powers equipment needed for life support, communication, scientific research, and maneuverability of vehicles for launch, landing, roving and other Space activities (Halpert, Frank, and Surampudi, 1999). A number of popular sources of electricity in Space include solar photovoltaics (PVs), hydrogen fuel cells, xenon fueled ion thrusters, and plutonium fueled radioisotope thermoelectric generators (RTGs).

Electricity from photovoltaic panels (PVs) has been used in Space almost from the beginning. The power produced is far too weak for lift off, but it can be used after attaining orbit or after escaping the Earth's gravity. Although Sputnik's radio signals in 1957 were powered by a silver zinc battery (Wall, 2020), one of the radio's in the U.S.'s second satellite, called Vanguard I, was powered by solar energy. The satellite was put into orbit by a Vanguard rocket in 1958. The one watt solar array had an efficiency around 10% (Flood, 2001). However, solar panels have their limitations. For some applications, the panels are shaded for part of the time. If too close to the sun, they must be shielded because of the intense heat or if too far from the sun (beyond Jupiter), the sun's rays are too weak for feasible use of currently make solar technologies. Thus, PV panels are typically paired with batteries or other sources of electricity. In Vanguard I, a second radio was powered by a non-rechargeable mercury battery, which ran out of power in a couple of months. The solar array generated power for about 6 years, but the satellite, itself, silently soldiers on (Garcia, 2017). The Russian Soyuz family of spacecraft, still used for human transport, has used solar panels since their first launch in 1966 (European Space Agency, n.d.).

Solar power was often paired with batteries, sometimes primary once through but more often rechargeable. The Soyuz spacecraft still uses rechargeable silver zinc batteries in conjunction with PV as did some early U.S. spacecraft (e.g. U. S. Ranger 3 and U.S. Mariner 2, both launched in 1962) (Bell, 2022; Dynamic SLR, n.d.). In 1959, the first nickel cadmium batteries were paired with solar panels in the short lived U.S. Explorer 6 satellite and others soon followed (Halpert et al., 1999; NASA, 2022f). In 1966, the first French satellite (Diapason) was equipped with solar panels and a rechargeable nickel cadmium (Ni-Cad) batteries by Saft (SAFT, n.d.). Ni-Cad batteries remained the most often rechargeable battery of choice to pair with solar PV for space use until the 1980's, when lighter weight, more powerful rechargeable nickel hydrogen batteries tended to become the PV battery partners of choice (Halpert et al., 1999).

The next popular break through was the lithium-ion battery first commercialized in 1991 and first used in Space by the European Space Agency (ESA) in 2001, when the ongoing Proba-1 satellite to observe Earth was first launched (ESA, 2019).Two of the five U.S. Mars Rovers used solar power coupled with lithium-ion batteries - U.S. Opportunity (2004–2018), and U.S. Spirit (2004–2010) (Ratnakumar, Smart, Whitcanack, Ewell, and Surampudi, 2014); the Parker space probe to study the sun used them as well (EnerSys, n.d.). Although the International Space Station (ISS) launched in 1998 used nickel hydrogen batteries for many years. fear for crew safety caused them to begin switching to lithium-ion batteries in 2017 (Arbin Instruments, 2019) with some solar panel upgrades in 2021 (ESA, 2021).

A solar power source that provides propulsion but not through the generation of electricity has been successfully deployed recently is a solar sail. The first was Japan's experimental spacecraft, the 310 kg Ikaros. It was successfully launched on another craft heading to Venus. Ikaros passed Venus before heading to deep space with last contact in 2015. It was designed to show that a spacecraft could be propelled in Space without an engine or fuel. Such a sail operates in much the same way as on a sailboat, except that light photons hitting the sail create momentum instead of the wind. Although photons provide a very soft push, it does not take much power to propel a ship through space. With enough time, impressive speeds can be built up with a solar sail. In three years, a craft powered with solar sails might reach speeds of 240,00 km per hour (150,000 miles per hour) with a laser assist the maximum approaching might approach 1/10 the speed of light. As of yet the weight being moved is very limited and is in the kg and not the tonnes. Tacking or changing the angle of the sail can be used for direction control. Nassau and the Planetary Society have also experimented with this technology (The Planetary Society, n.d.-b; Web Japan, n.d.), https://www.youtube.com/watch?v=Ndx_6J4uo2M, (https://www.space.com/9051-solar-sail-spacecraft-explore-solar-system.html, http://ffden-2.phys.uaf.edu/webproj/212_spring_2015/Robert_Miller/physics.html, https://science.howstuffworks.com/solar-sail.htm).

Another source of electricity in space is hydrogen fuel cells. In them, hydrogen is split into electrons and protons when it passes through a catalyst at the negative anode. The protons go through some sort of electrolyte, where electrons can't pass and are rerouted through a circuit producing electricity. The electrons and protons meet up again with oxygen at the positive cathode to become water (FCHEA, n.d.). See Department of Energy (n.d.), if you want to learn more about the different flavors of fuel cells and their advantages and disadvantages.

The first fuel cell used in Space was a polymer electrolyte membrane (PEM) fuel cell, which provided electricity for the last five of the 10 U. S. Gemini two-astronaut missions that orbited the Earth in 1965-66 (Smithsonian Institution, n.d.). Their efficiency was reportedly around 40 to 50%.The first use of an alkaline fuel cell was the U.S. Apollo 7 test mission that orbited the Earth in 1968 (Halpert et al., 1999; National Air and Space Museum, n.d.-a). Instead of a membrane these cells used the alkaline compound, potassium hydroxide, as an electrolyte and achieved efficiencies near 60%. They do not require precious metals as catalysts. But they do require pure oxygen instead of air at the cathode, if CO2 fouling needs to be avoided (Department of Energy, n.d.; Fuelcellsetc, 2013). Such fuel-cells were also used as the electricity source on the U. S. Space Shuttle Orbiter (Zona, 2010).

In choosing between fuel cells and solar panels, the weight of solar panels shifts to favor fuel cells for shorter missions, whereas the weight of hydrogen and oxygen fuel shifts the favor towards PV for longer missions. (Borogove, 2019a). Thus, the Mercury missions to put humans into short orbital flights, the Apollo Moon missions, or the U.S. Space Shuttle, making short trips to the ISS did not use solar power (Ash, 2022). However, recently, the privately owned Space X Dragon spacecraft, which makes deliveries to the ISS has incorporated solar panels as a power source (SpaceX, 2012)The new International Artemis Moon Mission started in 2017 is expected to land the first humans on the Moon in 2024. With this mission, there has been a resurgence of fuel cell research. Solid oxide fuel cells, which are more efficient, and regenerative fuel cells are being researched. With regenerative fuel cells, the water by-product is broken into hydrogen and oxygen by electrolysis fueled by solar power to be reused.

I have not found applications of these later two technologies. Regenerative fuel cells will likely find favor if the hydrogen can be generated in Space from water already available there. For example, beginning in 2008, instrumentation on India's Chandrayaan-1 mission orbiting the Moon, provided convincing remote evidence of water on the moon. Subsequent missions have confirmed that there is likely more than 600 billion kilograms of water ice at the lunar poles. Back of the envelope estimates suggest that the amount of water electrolyzed into hydrogen and oxygen could power fuel cell cars with current technology for 60 trillion km (36.5 trillion miles) (Mehta, 2020). Such discoveries put us closer to using the moon as a staging area for travel to mining sites.

Some water is likely available on Mars as well. Water as ice was verified on Mars by the U.S. Phoenix Mars lander in 2008 (Johnson, 2018). The U.S. Curiosity Mars Rover confirmed such water ice beneath the polar surfaces with some estimates suggesting it might be equal to the water trapped in the glaciers covering Greenland (Course Hero, 2022). The ESA-Russian ExoMars Trace Gas Orbiter, launched in 2016 has also found evidence that suggests a significant amount of water-ice may exist on Mars (Strickland, 2021). Upcoming planned Martian missions should give us a better estimate of the water available there.

Near Earth comets contain ice water as do carbonaceous chondrite asteroids. A collision with one of these objects may have provided the water on Earth, which accounts for only 0.05% of Earth's mass. Isotope comparison studies on water currently favor the asteroid theory (Bolles, 2022; O'Hanlon, 2019). Unfortunately, comets tend to have highly elliptical orbits putting them rather far from Earth much of the time. Thus, water is probably more plentiful in Space than earlier thought.

Ion thrusters are another option for propulsion in Space. In an electrostatic ion thruster, a fuel is ionized (given an electric charge) by bombardment with electrons. Most often the fuel is inert xenon with krypton a less popular choice. The bombarding electrons knock electrons off the propellant yielding positive ions. These positive ions are accelerated to very high speeds and expelled to produce the thrust to propel and maneuver the craft. Positive ions and electrons are reconnected upon exhaust so a charge does not build up in the spacecraft. If near enough the sun, the electricity needed to power this propulsion system comes from solar power. Ion thrusters only work in the vacuum of Space, do not have high thrust (acceleration), but have efficiencies greater than 90%. They work well in Space where high thrust is not needed for maneuvering but do not have enough thrust to overcome gravity on larger bodies such as the Earth or Mars.

If near enough to the sun, the electricity for ion thrusters can be generated from solar power. Maximum solar insolation (MSI) falling on a body orbiting the Sun decreases as we move away from the Sun according the following formula (Carrazana, 2018):

$$\mathrm{MSI} = \frac{\mathrm{L_{sol}}}{4\pi \mathrm{R}^2}$$

Where: MSI is measured in watts per square meter ($\mathrm{W/m^2}$)

Lsol=3.828×10^{26}

R=distance from the sun in meters

The above formula is the maximum which fall perpendicular to the absorbing surface without any atmosphere to absorb or reflect the solar radiation. The formula is applied to the planets in our solar system and Pluto in Table 2.

Table 2: Maximum Solar Insolation for Selected Bodies in the Solar System

Space Body	AU	R in Meters	$\mathrm{W/m^2}$
Mercury	0.39	5.83E+10	8948.879
Venus	0.72	1.08E+11	2625.626
Earth	1.00	1.50E+11	1361.125
Mars	1.52	2.27E+11	589.129
Jupiter	5.20	7.78E+11	50.337
Saturn	9.58	1.43E+12	14.831
Uranus	19.20	2.87E+12	3.692
Neptune	30.05	4.50E+12	1.507
Pluto	39.48	5.91E+12	0.873

Source: http://curious.astro.cornell.edu/about-us/56-our-solar-system/planets-and-dwarf-planets/general-questions/214-how-far-is-each-planet-from-Earth-intermediate; https://www.e3s-conferences.org/articles/e3sconf/pdf/2018/24/e3sconf_solina2018_00053.pdf.Notes: AU = an astronomical unit = 1.5×10^{11}. R is the distance of the space body from the Sun. $\mathrm{W/m^2}$ is the maximum solar insolation that falls on the body with no atmosphere.

These are maximum insolation such as we might expect at noon along the equator, if the body has not atmosphere. When averaged for Earth, the maximum average insolation is around 340 $\mathrm{W/m^2}$ (https://earthobservatory.nasa.gov/features/EnergyBalance/page2.php). Of this amount about 48% gets through the Earth's atmosphere to the surface (https://earthobservatory.nasa.gov/features/EnergyBalance/page4.php). From Table 2, you can see that maximum solar insolation from Jupiter and beyond is quite small. Further, the sun only shines on any given area part of the time.

Although conceived and experimented with much earlier, the first space mission that used electrostatic ion thrusters was U. S. Deep Space 1 (1998-2001), which flew by asteroid Braille, in the main asteroid belt between Mars and Jupiter, and by the Comet Borelly in the Near Kuiper Belt just beyond Neptune (NASA, 2008; Patterson, 2017). Later, the U.S. Dawn Mission (2007-2018) used ion propulsion to orbit the two largest bodies in the Main Asteroid Belt, he asteroid Vesta and the dwarf planet Ceres (NASA, 2021a)). Its ion system was powered by solar arrays with nickel hydrogen batteries using xenon as the propellant, while hydrazine also helped with maneuverability (NASA, 2022d).

The electromagnetic or Hall thruster, uses a magnetic force to ionize the propellant (Sforza, 2012). The Soviet Union developed and launched its first Hall thruster in a satellite in 1971. More than 100 of these thrusters were used by them in satellites in the next 30 years (Kim and Popov, 2004). They are still used on Russian spacecraft and have also been used by ESA, the U.S., and SpaceX (Amo, 2021; Dunbar, 2021;

Number, 2019). This thruster is more powerful than the electrostatic thruster and can operate on more different fuels but is typically less efficient (Singh et al., n.d.).

Nuclear energy has a long history in the Space movement. Most commonly nuclear Space devices are powered by the radioactive decay of plutonium. Radioisotope thermoelectric generators (RTGs) convert the heat of radioactivity to electricity. In this technology, the conversion is made with thermocouples, where temperature differences between two wires of different metals create an electric current. The temperature differences arise between the fuel and the surrounding atmosphere (U. S. Office of Nuclear of Energy, 2021). RTGs are robust with no moving parts requiring maintenance and can operate in harsh Space environments. They are favored for long missions, where the weight of solar panels or the absence of sufficient sunlight restricts the mission's objectives. (NASA's Jet Propulsion Lab, n.d.). (https://marspedia.org/Radioisotope_Thermoelectric_Generators:_Advantages_and_Disadvantages).

ESA has been working to develop RTGs powered by cheaper but less efficient Americium (Ambrosi et al., 2019). RTG units are sometimes referred to as nuclear batteries. As RTG power cannot be stopped or varied, other batteries are also typically included for times when power needs peak. RTG units are used when spacecraft need less than 700 W, about the wattage of a medium-size microwave. They have powered U.S. satellites as early as 1961 and Russian satellites as early as 1965. Versions of them have been used on missions to the moon and interplanetary travel including U. S. Pioneer 10 (1972-2003), which flew by Mars, Saturn, Neptune and left the solar system, U. S. Galileo (1989-2003), which orbited Jupiter, European/U.S. Ulysses (1992-2009), U.S. Curiosity Mars Rover (2012-2019) and U.S. Perseverance Mars Rover (2021–) which studied properties of the sun, China's Chang'e-4 (2018-ongoing) to explore the far side of the moon, and European/Russian ExoMars Rover, second stage to be launched in 2022 (American Experiment, 2021; ESA, n.d.-a; LaMonica, 2012; NASA, 2022e; World Nuclear Association, 2021). Current RTGs are far too weak to provide lift off from Earth, which might require on the order of 12 billion watts (Hypertextbook, 2022). Now that’s a lot of microwaves.

In some cases, the heat from radioactive decay is used directly in units called radioactive heat units (RHUs). As much of Space is typically very cold, such units keep equipment warm enough to remain functional. The U.S. Mars rovers –Pathfinder, Spirit, and Opportunity – were equipped with RHUs as was the Joint U.S. and ESA Cassini-Huygens spacecraft to Saturn. Sometimes both RHU and RTG’s are included as in the U. S. Galileo mission (Department of Energy, 2015; Dudzinski and Piazza, n.d.-a, n.d.-b).

Despite studying fission power systems for space travel over the years, the U.S. actually applied fission only once in 1965 in the SNAP 10A, a nuclear-powered satellite. Fission was not used to power the rockets for lift off but only to provide electricity to operate the satellite, which is still in orbit and operating under fission power. The Russians are thought to have powered numerous satellites with fission power, but again not to power rockets (Djysrv, 2019; World Nuclear Association, 2021).

Although science fiction writers are able to use fusion to propel their spacecraft, we have not yet harnessed this considerably more powerful energy source for such peaceful means. In nuclear fusion, two smaller nuclei are fused together to form a larger nucleus. The new mass is slightly smaller and a great deal of energy is released in the process. The problem arises in that it takes a great deal of energy to get the process going. With enough heat, the hydrogen atoms in gaseous form become a plasma of positively and negatively charged ions. If the positively charged ions get close enough together, they fuse rather than repel each other. In our sun and other stars, the stars stay very hot, gravity is very high, fuel (mostly hydrogen) is abundant and is continually fused to create helium. When the hydrogen is gone, the star continues on to the next phase in its life cycle, which varies depending on the star’s size (The Imagine Team, 2021) (Association, 2021).

So, where are we in trying to harness this technology to power our rockets? A few countries developed the technology to produce H bombs starting back in 1952. These bombs require a fission reaction to get them going, use fusion to produce their huge destructive power, have been used in warheads, but luckily have never been used in battle (Chan, 2019). For a sustained peaceful source of energy, the plasma must be prevented from expanding so much that fusion is not possible but no explosion takes place. Such containment is currently done with magnetic fields. Although heavier atoms up to iron can fuse, small atoms take less energy to do so. Currently, the fusion thought most likely to succeed commercially on Earth is between the heavy hydrogen atoms deuterium and tritium. Normal hydrogen (H) has one proton in its nucleus. Heavy hydrogen has added neutrons. If you fuse one deuterium atom (containing one added neutron-^{2}H) with one tritium atom (containing two added neutrons ^{3}H), you get one helium atom (He), one neutron, and lots of emitted energy.

However, there are a number of hurdles in producing energy from such a reaction. To get the reaction started requires very high temperatures. So high, in fact, that the very short reactions already achieved have taken more energy to get started than have been generated. Furthermore, the reactions attained have been quite short. (e.g. the Joint European Torus in the UK has attained 5 seconds of fusion and China's Experimental Advanced Superconducting Tokamak has attained 17 minutes of fusion (The White House, 2022).

For terrestrial use, deuterium is common and can be recovered from sea water with 1 out of 5000 hydrogen atoms being deuterium (Energy, n.d.). However, tritium is not. Work is being done to develop technology to breed tritium within the fusion reactor. This would be accomplished by enriching lithium atoms with the escaping neutrons. Each enriched lithium atoms break into one tritium and one helium atom. Lithium is also still rather plentiful on Earth. When such technology can be commercialized, it is argued it will provide abundant energy with fusion providing four times as much energy per kg of fuel as fission. It will also be safer, as the reaction will cease to function rather than meltdown in the event of a malfunction (Chatzis and Barbarino, 2021; Irfan, 2022).

Useable fusion has not yet been developed on Earth, nor has it been accomplished for propelling us into Space, but considerable effort is being expended towards it. When mastered for Space, the fusion power could be used to produce ions but with significantly more thrust than ion thrusters. It could cut the time to Mars from 8 months to around 3 months. Yet the current most promising research avenues for Earthly use are to use a tokamak reactor that uses ^{2}H and ^{3}H. However, such a reactor weighs 23,000 pounds and additional weight would also be needed to shield equipment and crew from radioactive tritium and emissions of high energy neutrons (R.A., 2019).

A current avenue of research for space fusion would use helium-3 rather than tritium. Helium-3, is lighter than helium with its nucleus containing the normal 2 protons but only 1 not 2 neutrons. Fusing deuterium and helium-3 results in normal helium and a proton. With a positive charge, the proton is easier to contain that the neutrons zipping about in the tokamak. Although more energy is required to get this reaction started than using ^{2}H and ^{3}H, no dangerous input or output is needed or produced. While the Earth has very limited supplies of helium-3 as its magnetic field repels these atoms, the Moon is thought to have more plentiful quantities of helium-3 blown in on solar winds as do some of our gaseous planets (Energy, n.d.; ESA, n.d.-b). Some seem to already be banking on helium 3 being commercially mined on the moon for Earth return. Not so long ago the U.S. Nuclear Corporation signed a Memorandum of Understanding with Solar Systems Resources to cooperate to mine helium-3 and lanthanide metals (often called rare earth metals) on the Moon for Earth return. The initial deliveries of He-3 are slated to begin by 2028 (DNews, 2011; Hewitt, 2015; Molvig, 2006; U. S. Nuclear Corp., 2021).

The record clearly indicates that we have the ability to go to Space, although payloads as yet are quite small by mining standards and costs are quite high. The payload for the U.S. Space Shuttle was only 25 tonnes into low Earth orbit (LEO). The record weight into LEO was about 141 tonnes, set in 1972 by a Saturn V rocket on a mission to the Moon. (Borogove, 2019b). The crewed lunar module on this mission landed an even smaller 16.5 tonnes on the Moon. (NASA, 2022b). The estimated cost of getting a kg into LEO on the Space Shuttle was $54,500. It has fallen significantly with the private sector entrance, and is now less than $3000 on SpaceX's Falcon 9 and falling (Duffy, 2022). Nevertheless, it would still cost you more than $550 to get your cup of coffee into LEO with you. The six Apollo missions that got to the Moon between 1969 and 1972 only brought back a total of 382 kilograms (842 pounds) of Moon rock. Other missions brought back even less.

The Soviets bought back 226.1 grams (0.5 pounds) of Moon rock on three missions from 1970-1976. In 2020, China's Chang'e 5, returned 1.7 kg (3.7 lb) of Moon rock from a volcanic area of the Moon (The Planetary Society, n.d.-a). The U. S. Perseverance project is projected to bring back less than 0.01 cubic meters of material from Mars (not much more than a fifth of a cubic foot) (Greicius, 2020). Wikipedia has a more complete list of samples including very small amounts from a comet, asteroids, and dust particles (Wikipedia, 2022).

Not just distance, but gravity, friction and other complications determine how difficult it will be to move larger amounts of material to, from, and across space. With Space travel, the first challenge is to achieve the acceleration needed to leave Earth's gravity. How much you need to accelerate depends on whether you are launching in the direction the Earth is moving or the more difficult task of launching in the opposite direction. You can launch into low earth orbit (LEO), (< than 2000 km above Earth), but if you accelerate further you can go to more distant places (Elburn, 2022). Acceleration is a change in velocity (v), which rocket scientists call delta v or abbreviate using the Greek letter into Δv. Delta v is measured in kilometers per second (km/s). Thus, every second we must increase velocity by an additional km/s yielding an acceleration of (km/s)/s or km/s2. Since the first forays into Space scientists have been computing idealized Δv's for a variety of trips between different celestial destinations. A selection of these Δv's are shown in Table 3.

Table 3 Idealized Δv between selected Space destinations

From	To	Delta v km/s
Earth, Lunar Destinations		
Earth Surface	Low Earth Orbit (LEO)	9.400
LEO	Geostationary orbit (GEO)	3.910
LEO	Earth C3=0	3.200
LEO	Earth L4, L5	4.100
LEO	Low lunar orbit (LLO)	5.400
LLO	Lunar Surface	1.600
LEO	Lunar Surface	6.400
Earth C3=0	LLO	0.700
Earth C3=0	Lunar Surface	2.300
Earth C3=0	Mercury C3=0	8.650
Earth C3=0	Low Mercury Orbit	11.590
Earth C3=0	Mercury Surface	14.650
Earth C3=0	Venus C3=0	0.640
Earth C3=0	Low Venus Orbit	3.580
Earth C3=0	Venus Surface	30.580
Mars and its two moons		
Earth C3=0	Mars C3=0	1.060
Earth C3=0	Low Mars Orbit	2.500
Earth C3=0	Mars Surface	6.300
Earth C3=0	Deimos C3=0	2.050

Earth C3=0	Low Deimos Orbit	2.052
Earth C3=0	Deimos Surface	2.056
Earth C3=0	Phobos C3=0	2.340
Earth C3=0	Low Phobos Orbit	2.343
Earth C3=0	Phobos Surface	2.351
Jupiter and four of its moons		
Earth C3=0	Jupiter C3=0	3.360
Earth C3=0	Low Jupiter Orbit	20.560
Earth C3=0	Jupiter Surface	65.560
Earth C3=0	Io C3=0	13.680
Earth C3=0	Low Io Orbit	14.410
Earth C3=0	Io Surface	16.260
Earth C3=0	Europa C3=0	12.250
Earth C3=0	Low Europa Orbit	12.830
Earth C3=0	Europa Surface	14.310
Earth C3=0	Ganymede C3=0	10.030
Earth C3=0	Low Ganymede Orbit	10.820
Earth C3=0	Ganymede Surface	12.790
Earth C3=0	Callisto C3=0	8.500
Earth C3=0	Low Callisto Orbit	8.570
Earth C3=0	Callisto Surface	10.330
Saturn and one of its moons		
Earth C3=0	Saturn C3=0	4.500
Earth C3=0	Low Saturn Orbit	14.730
Earth C3=0	Saturn Surface	44.730
Earth C3=0	Titan C3=0	7.560
Earth C3=0	Low Titan Orbit	8.220
Earth C3=0	Titan Surface	15.820
Planets beyond Saturn		
Earth C3=0	Uranus C3=0	5.280
Earth C3=0	Low Uranus Orbit	14.730
Earth C3=0	Uranus Surface	44.730
Earth C3=0	Neptune C3=0	5.390
Earth C3=0	Low Neptune Orbit	11.510
Earth C3=0	Neptune Surface	29.510
Asteroids landed on or approached closer than 100 km and date/s of rendezvouz in parenthesis		
LEO#	9969 Braille (1999)	10.931
LEO#	433 Eros (2001)*	6.112
LEO#	25143 Itokawa (2005)*	4.637
LEO#	4179 Toutatis (2012)	6.590
Earth Ceres Transfer	1 Ceres (2015)	4.810
LEO#	162173 Ryugu (2018)*	4.663

LEO#	101955 Bennu (2020)*	5.096
Notes: * indicated asteroids that have been landed on, #substract 3.2 from Δv if leaving from Earth C3=0		
Sources: https://en.wikipedia.org/wiki/List_of_minor_planets_and_comets_visited_by_spacecraft; https://space.stackexchange.com/questions/41432/is-going-to-ceres-as-easy-as-going-to-mars-like-this-aerospace-engineer-says; https://external-preview.redd.it/47Z8OHKj-8BImmr3bDRgrnponXxglbBbLvz0dy_3SV8.png?auto=webp&s=8f4f3021734794c6b841311f248c98b575494568; https://www.reddit.com/r/space/comments/29cxi6/i_made_a_deltav_subway_map_of_the_solar_system/; https://infogalactic.com/info/Delta-v_budget; https://www.asterank.com/; https://letstalkscience.ca/educational-resources/stem-in-context/escape-velocity		

To get from the Earth's surface to low Earth orbit (LEO), the Δvs start at around 9.4 km/s. The majority of artificial Earth satellites and the ISS are in LEO, which are at distances of 2000 km (1200 miles) or less from Earth (https://www.space.com/low-earth-orbit), https://www.nasa.gov/leo-economy/faqs). With more acceleration, we can go into a higher orbit synchronized with the Earth's rotation (geosynchronous orbit (GSO)) putting us roughly above the same spot on Earth at all times. If this GSO is over the equator, not only is the same spot always below, but the whole visible area is always the same. Such orbits are at distances around 36,000 km (22,356 mi) from Earth. GEO requires an additional Δv of 3.8 from LEO. GSO and GEO are orbits typically used for communication satellites and surveillance (https://solarsystem.nasa.gov/basics/chapter5-1/).

An orbit that gets us from one Space body to another with the lowest Δv, which typically minimizes fuel burn, is the Hohmann transfer orbit. From this orbit of the originating body, we transfer to an orbit of the destination body. Such an orbit for Mars would be called Earth Mars transfer orbit https://www.planetary.org/space-images/hohmann-transfer-orbit; http://jwilson.coe.uga.edu/EMAT6680Fa05/Bacon/hohmanntransfers.html; (Jet Propulsion Laboratory, n.d.-b)

Another handy category of orbits are Lagrange points. These refer to orbital positions of an object relative to other bodies also in orbital relationships. They are somewhat similar to geosynchronous orbits, but they magically remain over the same position with respect to more than one celestial body. For example, the moon orbits the Earth and the Earth in turn orbits the sun. There are five points in orbit around the Earth that remain in a fixed spot over both the Earth and the Moon. Two of them are stable. If a satellite is orbiting at either of the stable two points, called L4/L5, and wobbles off course, there are forces to push it back on track. If located over the unstable points (L1/L2/L3) more guidance systems would be required to keep them on course (NASA/WMAP Science Team, 2018). Such Lagrangian points are logical points for refueling and resupply depots servicing space mission. To get to the Earth-Moon L4/L5 from LEO requires Δv of 4.1.

If we want to leave Earth altogether from LEO, add a Δv of 3.2 to the 9.4 Δv to get to LEO. Then we can reach an altitude and speed where the Earth's gravity does not exert enough force to pull the craft back. This distance for Earth is called Earth intercept, Earth C3=0, or Earth escape/capture. At this altitude the energy of the accelerating craft offsets the pull of gravity. Once past this point, the spacecraft can escape into space and will continue to coast until acted upon by some external force (New World Encyclopedia, n.d.). Similarly, there is such an intercept for each Space body. The Δv to get to its C3=0 from the surface is quite small for asteroids (e.g about 0.5 km/s for asteroid Ceres (https://upload.wikimedia.org/wikipedia/commons/9/93/Solar_system_delta_v_map.svg) but rather impressive for the likes of Jupiter shown in Table 3 (Δv from the surface to Jupiter C3=0 is 62.2 km/s).

Once we get to Earth C3=0, an additional 0.7 would get us to low lunar orbit (LLO) but considerably more (Δv=2.3 or a Δv of 6.4 fro LEO) would be required to land on the Moon. Here gravity is the culprit. To accelerate and leave a body with gravity requires enough acceleration to escape the gravity. Likewise to slow down and not crash land will require a similar amount of Δv to decelerate.

If the space body has an atmosphere, aerodrag will create friction and slow the craft requiring more Δ to take off and less to land. This drag may be used for aerobraking. However, aerobraking creates rather a lot of heat with temperatures exceeding 1500°C are not uncommon for Earth landing. If aerobraking is used, unless the craft is being crashed for disposal, heat shields are required. Otherwise the craft will meet the same fate as falling meteorites with much of its mass incinerated. When designing craft and missions, both the added weight of the heat shields and reduction in Δv from aerobraking will need to be considered. If the atmosphere is used to slow a craft enough to put the craft in orbit around a body, the maneuver is called aerocapture. This too can reduce Δvs (Bluck, 2011).

All planets in our solar system have some atmosphere, but they vary considerably and would provide different degrees of aerobraking. Mercury's atmosphere is almost a vacuum, Venus has a thicker and Mars a thinner atmosphere than Earth, while Jupiter, Saturn, Uranus, and Neptune have rather thick and deep atmospheres thicker than Earth. https://scied.ucar.edu/learning-zone/atmosphere/what-is-atmosphere. Although our Moon and the asteroids typically do not have atmospheres, some of the other moon's in the solar system are known to have some atmosphere, but they tend to be thin and only Saturn's Titon has an atmosphere heavier than Earth with an atmosphere pressure of 1.4 bars (https://www.planetary.org/articles/04081101-a-moon-with-atmosphere).

Table 3 also shows Δvs for seven of the asteroids we have landed on or come in close contact with (less than 100 km). Four of them have lower Δvs from Earth C3=0 than the Moon (Itokawa, Ceres, Ryugu, Bennu). From such visits as well meteorites and telescopic viewing, information on asteroids has been accumulating. Asterank (2022), Digg (2017), and NASA (2022h) give the Δvs from LEO for more than 17,000 Near Earth Asteroids (NEA).

Asterank has a database of more than 600,000 asteroids. Based on spectral composition, orbital information, and mineral prices, they list names, information on the asteroid's orbit, asteroid group, nearest pass to Earth, and Δv's. For some, they estimate mineral values and mining profits. At least 2000 of the listed asteroids have required lower Δv's than landing on the Moon. Their low gravities require less energy to slow down their approach or accelerate on leaving. These low Δvs are the reason Cole and Cox (1974), O'Neill (1974), Lewis (1996) and others have suggested that NEAs might be the desired first targets for Space mining.

However, landing will require synchronization of the craft with the spin and angle of the asteroid. With inertia, each increase of decrease in speed or change in direction require additional Δv. The total Δv equals the sum of the Δvs for all maneuvers. Further, the Δvs reported are for launch windows with optimal orientation to the asteroid, which may only occur every few years.

In computing Δvs, we can turn to Tsiolkovsky's ideal rocket equation, published way back in 1903 (https://www.nasa.gov/audience/foreducators/rocketry/home/konstantin-tsiolkovsky.html). He computed amount of Δv generated from a rocket from the rocket mass (M_{s0}), fuel mass (F_0), and the exhaust velocity of the rocket (v_e) assuming no drag and constant fuel burn over time as

$$\Delta v = v_e \ln\left[\frac{Ms_0 + F_0}{Ms_0}\right] \qquad (1)$$

(Core, 2015; Spakovszky, 2007).

The velocity (v_e) is determined by physical principles and the rocket's design. See Benson (2021) for highlights on the determination of v_e. The amount of fuel needed per kg of payload to reach these destinations depends on the rating of the particular rocket. Rocket ratings are typically the amount of velocity change it can manage by burning its entire fuel supply. The Δv may be influenced by gravity, if the rocket is operating near large objects or drag if the nearby object is large enough and cool enough to have an atmosphere (Astronomynotes, 2022). For example, the return to Earth from the moon would require a lower Δv as the moon has less gravity to oppose the lift off and Earth has more atmospheres to slow the ship down. Drag from an atmosphere and gravity adds Δv when accelerating or moving away and decreases Δv when decelerating or moving towards a large object.

To illustrate how Δv changes in equation (1) as you add more fuel to a given rocket, take the case of the space shuttle with a v_e of about 4.5 km/s (https://www.centennialofflight.net/essay/SPACEFLIGHT/rockets/SP6.htm) The main engines of shuttle burned LOX and LH2 at a ratio of fuel mass 83% and rocket mass 17% (https://www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.html). Apply this ratio to move 17 metric tonnes (mt) into space using 83 mt of fuel. Inserting into our rocket equation, we find we will be able to accelerate this mass to the Δv rate of

$$\Delta v = 4.5 \ln\left[\frac{17+83}{17}\right] = 7.973 \text{ m/s}$$

Thus, this rocket could accelerate our 17 mt to an ideal Δv of about 8. This was not enough to get into LEO to the international space station. The Space Shuttles has some second stage booster rockets using solid fuel that finished the job (https://www.nasa.gov/returntoflight/system/system_SRB_prt.htm). Figure 1 shows what happens as we add more fuel to move the 17 tonnes. Notice how the amount of Δv generated increases at a much slower rate that the increase in fuel. For example, doubling the amount of fuel from 83 to 166 only increases the Δv by a about 34%. This dramatic reduction in the rate of Δv added for increases in fuel is sometimes referred to as the "tyranny of the rocket equation" (https://www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.html)

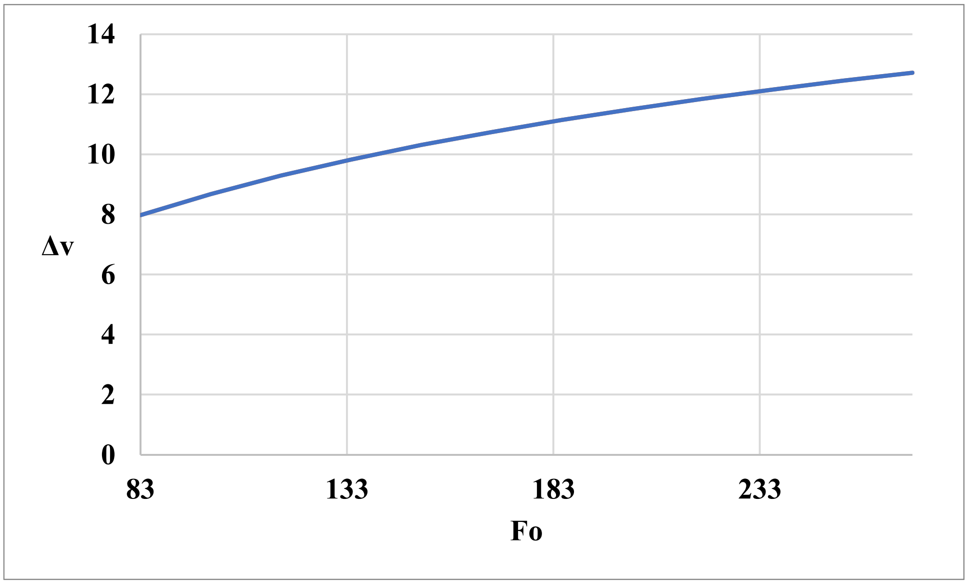


Figure 1 What happens to Δv as we add fuel all else equal

Notes: Computed using equation 1, with ve=4.5 km/s and M_0=17 tonnes.

Similarly, we can visualize what happens as we add more weight to a given amount of fuel in Figure 3. Doubling rocket weight reduces Δv by less than ½ and the relate rate of decline diminishes as we keep adding more weight.

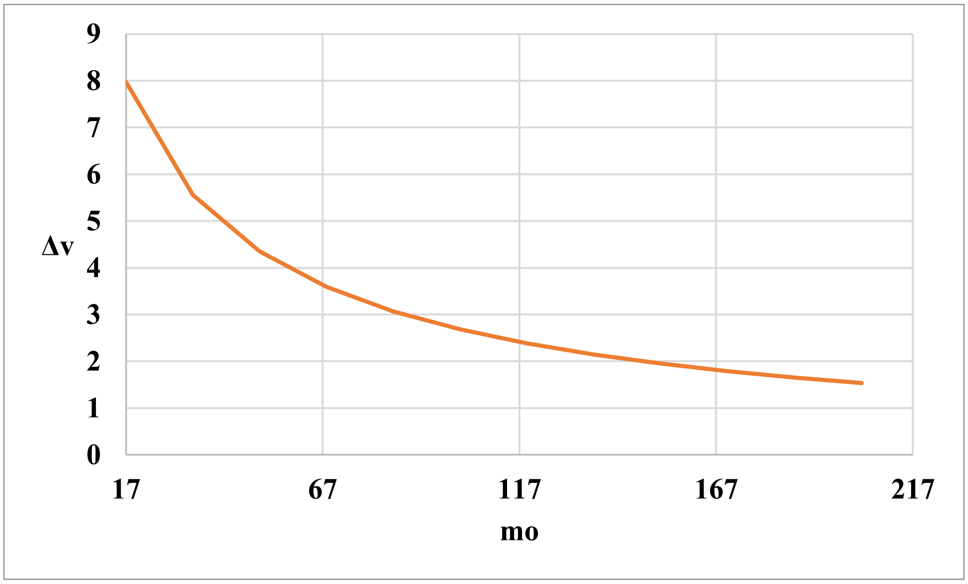


Figure 3 What happens to Δv as we add rocket weight all else equal

Notes: Computed using equation 1, with ve=4.5 km/s and F_0=83.

If you know the design of your rocket and the Δv required to get to your target mining operation, you can compute how much fuel you will need to get there as follows:

$$\frac{\Delta v}{v_e} = \ln\left(\frac{Ms_0 + F_0}{Ms_0}\right) \rightarrow \exp\left(\frac{\Delta v}{v_e}\right) = \frac{Ms_0 + F_0}{Ms_0} \rightarrow Ms_0 \exp\left(\frac{\Delta v}{v_e}\right) = Ms_0 + F_0$$

$$Ms_0 \exp\left(\frac{\Delta v}{v_e}\right) - M_{S0} = F_0 \qquad (2)$$

Notice that the fuel needed increases linearly with the rocket mass including its payload. If we double the weight, we want to get into space, all else equal we double the fuel needed. Or doubling the fuel used, will double the weight we can ship to our destination. However, the relationship between Δv and fuel is more interesting and we can do some simple computations using some of the Δv's in Table 3. Referring back to Table 3, the most favorable Δv to get from Earth to LEO is 9.4, which exceeds the additional Δv to get from LEO to land on the Moon (6.4) and approaches the additional Δv (10.1) to land on Mars. This demonstrates the advantage of having mining, processing to final end-product and material use all in Space and above LEO if other costs are manageable.For a rough illustration, assume a v_e of 2.4 and a rocket mass with payload of 130 tonnes. Taking lift capacity as rocket mass and payload, these values are similar to those for a Saturn V at take off from Earth's surface heading to the Moon (https://iu.pressbooks.pub/openstaxcollegephysics/chapter/introduction-to-rocket-propulsion/, https://apollo11space.com/how-much-did-saturn-v-weigh/). Table 4 shows the fuel needed at Earth takeoff under a single stage rock under ideal conditions for three potential near term Space mining targets: Lunar surface (Δv=14.9), Mars surface (Δv=18.9), Ryugu (Δv=14.1)). It demonstrates the dramatic exponential increase in fuel use at Δv is scaled up

Table 4: Estimated Tonnes of Fuel Required from LEO to Moon, Mars, and Ryugu

To:	Δv From Earth Surface (km/s)	F0 from Earth Surface, tonnes	F0 From LEO
LEO	9.4	6400.3	0.0
Moon Surface	14.9	64463.4	1155.9
Mars Surface	18.9	341859.2	6678.1
Ryugu	14.1	46153.2	791.4

Notes: Computed using equation 2, with ve=2.4 km/s and M_0=120

Asterank estimates the potential for valuable minerals in the asteroids, where such information exists. In their list of 300 most cost effective asteroids in terms of mining values, they have considered both the Δv and the mineral potential. Of these 300 most accessible, 20 have Δvs from LEO less that for landing on the moon**5. Developing, producing, and processing material**

After finding our mineral targets, we need to go get them and turn them into saleable products. In this section I consider how we would go about these steps on Earth. The types of minerals we mine are often divided into different categories. In this paper, I categorize them in four ways: industrial minerals, fuel minerals, metallic minerals, and gems. Industrial minerals are not metals or fuels or chemical compounds. They are widely used but have low unit value. They include basic building material (sand, crushed rock, clay) and other useful products (phosphates for fertilizer, salt used as a flavoring, preservative, and input into many chemical and other products, etc.) (AGI, n.d.; Earthresources, 2021). On Earth, such low unit value products are abundant and must be found in fairly concentrated deposits and require minimal processing to be commercially feasible. They are most often surface mined. Although abundant and relatively cheap on Earth, given their bulk they would be quite expensive to transport for use in Space. If we start building habitats in space, we can expect to especially need building products from this category.

Fuel minerals include coal, uranium, oil, and natural gas. Only coal and uranium are mined and are initial candidates for inclusion in the scope of this chapter. Since we believe coal formed from plant materials millions of years ago, it is not a likely mining target in our solar system, so will not receive much attention. Further oil, is also thought to have come from organic life and is not a likely target. Natural gas on Earth is thought to be mostly of organic origin as well. However, methane (CH4) is very abundant in our solar system and occurs as a gas, liquid, and solid. It is currently thought that methane in space might have formed from carbon and hydrogen banging into dust particles in Space (Leiden University, 2020). It is not so abundant in the other inner planets (Mercury, Venus, and Mars, but it is abundant in the outer planets beyond Mars. It is contained in the atmosphere's of Jupiter, Jupiter's moon Titon, Uranus, Venus, and is often frozen in comets (Guzmán-Marmolejo and Segura, 2015). Methane might eventually be considered for mining from Space as a fuel or source of carbon and hydrogen, but oxygen, water and hydrogen-3 seem to more accessible and likely nearer term targets.

A third category of minerals is metallic minerals. They may come as base metals, but are more often bound in chemical compounds such as oxides (containing oxygen atoms), sulfides (containing sulfur atoms) or halides (containing halogen compounds - fluorine (F), chlorine (Cl), bromine (Br), and iodine (I)). (Science Learn Hub, n.d.). They are more typically found in hard rock and may be surface or underground mined. If they exist in a compound, the compound is separated and concentrated and sent on to a smelter or refiner to separate out the metal. Evidence is mounting that metals are available on the Moon, Mars, and in NEAs (Howell, 2020).

The cheaper industrial metals we currently mine and use are abundant on Earth. They are used to produce infrastructure and are inputs into many of the products that are considered essential in current industrial society. The top 4 such metals ordered by millions of tonnes produced in 2019 are aluminum, manganese ore, chromium ore and concentrate, and copper. For both manganese ore and chromium ore, much of the concentrated ore is sold directly to steel makers (Bhutada, 2021; Department for Energy and Mining of South Australia, n.d.; The Editors of Encyclopedia Britannica, n.d.-a). These 4 minerals comprised over 80% of industrial metals production in 2019. It is unlikely these would be early space mining targets for Earth return, but such metals do exist in nearby Space and could well be targeted for use if human habitation and industrial production develop in Space. However, the much higher priced precious metals (gold and the platinum metal group metals (PMG), if mined as by products for other more basic metals or products used in Space, might be a possibility. However, more than 62 million metric tonnes of aluminum were mined in 2019 at a price of less than $1800 per metric tonne, whereas less than 3500 metric tonnes of gold were mined at an average price of $ more than 50 million USD per metric tonne (Garside, 2022; Knoema, 2021; O'Neill, 2022). Palladium and platinum production also priced in the millions of dollars per tonne sell even less tonnage per year. Care would need to be taken to understand what an infusion of these precious metals into Earth's market would have on the price.

My fourth category is non-biological gemstones. Most such gemstones are crystals, which means they have well-ordered and repeating atomic structure. Most are formed underground from heat and/or pressure, sometimes deep within the Earth as for diamonds. Such deep deposits may get to the surface with volcanic eruptions flinging them closer to the surface. Less common are the gems built up by sedimentary deposits such as opals (Australian Museum, 2022; Clark, n.d.; Gem Rock, n.d.). Increasing clearness, hardness, size, and scarcity tend to increase a gems value. Although Edison's planet made of diamonds is probably not nearby, there is some evidence that gems are available in Space and suitable environments exist in Space to create some of them (Yasinski, 2021). However, as with precious metals one could imagine that if those most valuable gems are a byproduct of other mining for Space use, they could be targeted for Earth return. However, as rarity is one of the aspects that enhance their value, again care would need to be taken to not flood the market.

For small operations of loose material on or very near the surface, materials may be scrapped or raked up being careful to contain the results from floating off if there is no gravity. Excavators that chew and collect material are a likely option. Augers may be another option and have already been used in Space for sampling. See Longchen, Songcheng, and Hui (2014) for the use of augers in space sampling and optimal drill structure. On Earth augers may have bits up to a meter across and go to depths of around 100 meters (Bhattacharyya, 2020). As always, our methods will have to adapt to low gravity harsh conditions and the available energy supply. Explosion driven impactors have been used in Space to loosen material near the surface for collection.

Let's consider these processes in more detail and see what we know of these processes on Earth. Earth mining started with surface mines and more than 80% of Earth's mined material still comes from surface mines with the remainder coming from underground. Such mines typically have cut off limits less than 300 meters deep, below which it becomes uneconomic to continue in mining (Layton, 2022). It seems likely that our space mining ventures will start with surface mining, as well. Ali Elbeblawi et al. (2021) notes that open pit and open cast are the most common techniques on Earth. Other such mechanical methods include quarrying, strip, and auger mining. They note a variety of aqueous or water based mining methods including - placer, dredging, hydraulic, solution, and in situ leaching.

Let's learn a bit more about all these methods and consider their potential for Space. With open pit mining, as we continue, we typically go deeper and deeper. Waste and overburden need to be moved to an external dump to be out of the way with reclamation deferred until the mine is nearing or is depleted. Such reclamation can be quite costly but may not be required in early space mining ventures, especially if they are on non-inhabited bodies. Open cast mines are similar to open pit but are horizontal enough to allow overburden to be cast into mined out areas as we go along. With long and shallow deposits we might strip mine, with long strips mined out and overburden and waste again left in the mined out areas. Thus, reclamation can again proceed as we go along. These later two methods seem to be more desirable space methods, if we can find ore deposits where they are appropriate unless absence of gravity means the waste floats up and blocks our vision or interferes with the mining process. The amount of reclamation on abandoned mined areas might be minimal at first, if human inhabitants can just mine and move on .

Quarrying relates to the collection of rock for construction. How it is done depends on the deposits and end use needs. The Moon, Earth, and other bodies, contain regolith, which is loose rocky material of varying sizes on top of bedrock or more solid material. If the regolith is fine enough, it may be scooped up and used directly for construction. More likely, it may need to be sorted or crushed for more homogeneity. If it comes in large sizes that can be used to make homogenous blocks of specific shape, such as for marble facing, it may need to be split, sawed, or cut to the appropriate shape. In auger mining, a spiral cutting tool run by a motor drills into thin seams. The mined material moves up the spirals to the surface for further processing.

In all these cases, our above ground space activities often parallel our astronaut's activities, when collecting moon rock, but would be at a much larger scale. We will need to rake or scrap away over burden, collect and scoop up material into transport containers. Ore may need to be broken or crushed for collection and further processing but not likely with a hammer as wielded by humans on the Moon.

With aqueous methods (e.g. placer, dredging, hydraulic, and in situ leaching) water is needed sometimes in conjunction with other chemicals. Elbeblawi et al. (2021). Placer, dredging and hydraulic mining are these typically aimed at placer deposits. Heavier minerals in such deposits that are not dissolvable by water are carried and deposited by running waters or sometimes wind, with lighter minerals carried away. The early traditional mining method for placer deposits was panning. In more productive sluicing, gravel is shoveled into a sluice box. Often these are called pinched sluice boxes as the boxes gradually narrow from the feed to the discharge end. Water washes out lighter minerals while small barriers at the end of the sluice box slow the water enough to let heavier valuable materials settle out.

With dredging, the equipment varies depending on whether the material is above or underwater. It typically involves loosening and sucking up water laden material. This material ends up in a washing plant that continuously separates out valuable material and discards the tailings. Hydraulic mining uses high pressure water to loosen deposits and wash them into a sluice box, while waste, potentially environmentally damaging, is washed away.

Although water for propellant may be one of the earliest mining targets (Sowers and Dreyer, 2019), given the lack of stable free running water in the near-term solar system targets -- Moon, Mars, and NEOs-- these aqueous techniques may not be used in space mining methods in the near term. Such techniques also typically rely on gravity. Of the more than 10,000 known NEOs, the largest is 41 km across with a gravity 0.0089 that of Earth (Kramer, 2013). So these techniques would likely not work on NEOs. Nor would they work on the two Martian moon's, Deimos (diameter 12 km or 7.5 miles) and Phobos (22 km or 14 miles).

In situ leaching, probably had its origins in heap leaching to recover materials left in waste heaps or in ore leached underground and brought to the surface. In the U.S., it was first applied in Nevada for the recovery of gold (Ong, 2019). With in situ leaching, liquids are pumped into deposits, pumped out carrying the desirable material, which are then are separated from the liquid. If the desired material is water soluble at normal temperatures, the liquid used may be water at normal temperatures as is the case for salt. If the mineral is water soluble but has higher melting point, heated water (as is the case for potash) superheated water (as in the Frasch process used to produce sulfur from salt domes on Earth). Steam techniques have has been used for heavy oil production since it was first applied in Venezuela in the 1960s (Rigzone, n.d.).

If the desired material is in hard rock and is not water soluble, other liquid or gas solvents called lixiviants may be used. The lixiviant chosen will depend on the materials in the ore bodies, the cost, environmental regulations, recyclability, etc. Common lixiviant examples include sulfuric acid for copper and a combination of hydrogen peroxide as an oxidant and sulfuric acid as a complexing agent for uranium. More than half of uranium produced is mined in situ (https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/in-situ-leach-mining-of-uranium.aspx). However, if such chemicals needed to come from Earth, mechanical methods would seem to be a more likely alternative. Although with recycling, the chemicals might be accumulated over time, if these methods proved advantages and the ability to produce the chemicals locally would certainly change the economic possibilities.

A number of authors believe that water for propellant may be our first mining target in Space. Sonter (1996) cites a number of earlier studies promoting this idea. More recent proposals for water mining include Sowers and Dreyer (2019), Bagrov and Leonov (2018), and Jamasmie (2019). If the water is free form it will be ice in all our near-term targets. If it is far below the surface, then some sort of in situ method using heat might be a consideration. If it is near or on the surface, it would seem mechanical options would be used for collection with melting and purification to follow.

situ mining may also require increasing the permeability of the source rock by blasting, hydraulic fracturing or other means. Now our astronauts did blast in some cases, and it seems likely that such methods will continue when we scale up from minute samples to commercial ventures.

Although the U.S. sent human's, Soviet lunar samples were obtained robotically. Their lunar lander was equipped with a drill connected to the end of a sampling arm. The arm placed the sample in a return capsule that was launched to Earth (Lewis, 2020). Fast forward 44 years to the quite recent Chang'e 5 mission in 2020, which robotically collected moon samples using a scoop and drill. The ascent vehicle transferred the sample to the Earth-return capsule in the service model in lunar orbit. The service model released the return capsule to land on Earth and continued on to the remainder its mission (The Planetary Society, n.d.-a).

Some NEOs have been sampled as well. Dust from the comet Wild 2 was captured by the U.S. Stardust mission during a flyby and returned to Earth in 2006. The dust was caught in a low density, high porosity silica aerogel or smashed onto the aluminum frame around the aerogel After the desired exposure, the collector was folded back into the protective return capsule (NASA, 2022a). This method does not seem so likely for mining, but on low gravity objects, we will need a way to capture the mined material before it can float away. Japan's Hayabusa mission to the asteroid Itokawa ($\Delta v=4.29$) was the first mission to actually land on an asteroid and return a sample back to Earth arriving in 2010. Its planned collection method did not work properly so they could only collect a small amount of surface material from dust stirred up when the craft landed (NASA, 2022g).

Two later asteroid sampling missions seem to be faring better – Hayabusa 2 and OSIRUS REx. Both used an explosion driven impactor to loosen material beneath the surface for collection (Asteroidday, 2020). The collection method worked as planned for Japan's Hayabusa 2 mission. The explosive, called octogen, created a crater on Ryugu ($\Delta v=4.66$), and a landed craft was able to collect some of the loosened material for Earth return in 2020 (Williams, 2019). The U.S, OSIRIS REx mission was not able to land on Bennu ($\Delta v=5.1$) because it was more boulder ridden than expected. It was able to use a robotic arm to blast the surface with nitrogen gas and vacuum up a sample. The sample is scheduled for Earth return in 2023 (Thompson, 2020).

These more recent examples also give us some ideas about mining in Space. All used robots and given the difficult conditions on our near mining targets, it seems likely that robotic mining will be a strong near term option. Although crewed missions to the Moon and Mars seem to be the cards in the coming two decades. Our robotic miners may have some light supervision in these cases. We will know more as the plot unfolds and the crew inhabits off-Earth object for awhile. These missions suggest we can get to our targets and collect samples, while advances in artificial intelligence continually advance that probability.

Yet these samples were tiny and no processing was done on the samples. Can we do this collection at scale, add in processing, and do it at commercial levels is the question.

If our surface deposits go quite deep, and we have depleted the feasible surface mineable deposits, we may move underground. For example, the deepest open pit mine on Earth is the Kennecott Copper Mine in Utah at 1.2 km deep (Nesfircroft, 2022), while the deepest underground mine in the world (AngloGold Ashanti's Mponeng gold mine) is more than 3 times deeper (Mining Technology, 2019). But most mines are considerably less deep than these two extremes (Layton, 2022). For example, most surface mines do not tend to go deeper than about 300 meters (about 980 feet) (Layton, 2022). Going deeper becomes considerably more costly and complicated. (e.g. EIA (2021) reports U.S. above ground productivity in 2020 averaging in excess of 18,000 metric tonnes per year per employee in 2020 but less than half that when mines are underground.

Tunneling for underground mining seems less likely at first, unless the needed materials are deep beneath the surface or the tunnels once mined out are then used as well shielded habitats. For the very smallest asteroids tunneling may be infeasible or unnecessary. Many decades ago, (Cole and Cox, 1964) suggested hollowing out asteroid up to 30 km in diameter to provide rotating space habitats. Between these extremes, some have suggested that the asteroid could be converted into space ships to provide transportation for humans, mineral ore and mineral products. (For example, Made In Space, acquired by Redwire in 2020, received NASA funding in 2016 to look into turning asteroids into space craft in a project called Reconstituting Asteroids into Mechanical Automata (RAMA). Such craft could be made from asteroids with diameters of 10 m to 100 m or, perhaps even higher (https://redwirespace.com/newsroom/redwire-acquires-made-in-space-the-leader-in-on-orbit-space-manufacturing-technologies/?rdws=nnn.xffxcv.tfd&rdwj=120; https://3dprint.com/218874/made-in-space-project-rama/, (Dunn, Fagin, Snyder, and Joyce, 2017)).

Of the almost 29,000 NEOs currently catalogued by the Minor Planet Center, the largest, 1036 Ganymede, is only 41 km long, while the vast majority (>97%) have an estimated diameter of less than 1 km. The smallest asteroid in the database has an estimated diameter of less than a meter. Since the largest are typically found first, the continuing inventory grows will likely be even more heavily dominated by smaller objects. Elvis (2013) suggests that if water and PGMs are the mining targets, then 85% of NEAs are stony and unlikely to be near term mining targets. He estimates that potential mineable targets and their percent of the total NEAs to be: water rich @ 3%, carbonaceous @ 10%, metallic @ 5%, and platinum rich @ 1%). His targets for PGMs would have diameters greater than 100 meters and those for water would have diameters greater than 18 meters. Metallic asteroids are likely to have the structural integrity for habitats even if relatively small, other types may not.

Mining such asteroids or converting them into craft will require the appropriate technologies that will likely be modifications of the many techniques used on Earth. Such techniques are designed depending on the mineral, its properties, its concentration, its orientations and its environment. But despite all these variations, underground mines generally start with the tunnels used to get miners and equipment and minerals to the surface. Such tunnels must be made safe while effectively proving access to the targeting material. Such tunnels and ore are typically created by combinations of drilling and blasting, which has been used on a very small scale in Space.

If the tunnels are mostly vertical, they are called shafts. If they are slanted passages they may be called declines or ramps. If they are mostly horizontal and follow the ore body, they may be called drifts. Drifts are typically created by drilling, blasting, removing the broken material, scaling any loose material left on the drift wall and adding any needed re-enforcement to prevent collapse. Cuts are drifts that are using to mine the ore with crosscuts going through the ore being mined, undercuts going beneath the current ore being mined and top cuts or top sills going above the ore. Stopes are open areas that give access to ore or are areas from which ore has been mined (Britannica, n.d.-a; Layton, 2022; U.S. Securities and Exchange Commission, 2022).

If the ore is being mined underground in soft rock (1) room and pillar (a more selective technique) and (2) long wall, a bulk method are often favored. If the ore is being mined in hard rock underground, more methods are typically considered. The method chosen depends on the desired mineral, its properties, its host ore and the host rock as well as the orientation of the ore in the host rock. Choices include cheaper bulk mining for large deposits with low grade ores or more expensive selective mining for high value minerals spread more thinly throughout the ore. The quality of the surrounding rock will determine whether artificial support will be needed in the tunnels and mining areas or not (Dutton, n.d.). Just as we may change from above to underground mining across time, a variety of techniques may be employed across time and space in the same mine. Let's now proceed to consider some these various mining techniques.

Flat deposits in soft rock, such as for coal, salt or oil sands, may be mined by creating a room from mined ore dislodged by traditional drilling and blasting or by a continuous miner that grinds loose the ore and loads it continuously. Pillars are left to support the rooms until the last pass through to recover the ore in the pillars and let the roof fall in. These pillars give the room and pillar name to this technique. In some cases, roof bolts may provide enough support and will be removed upon completion of the ore removal. If subsidence is a problem the pillars may be left to provide support. For a nice video of the room and pillar technique, see (Dutton, 2020). With long wall mining in soft rock, a large piece of equipment, shears off ore that falls on a conveyer for transport to the surface, the roof is supported by hydraulic lifts until the shearer passes on and the roof is allowed to collapse (Department of Environmental Protection, n.d.).Hard rock underground mines more typically contain metals and gems. The method employed depends on the layout and properties of the ore, mineral sought after, and the host rock. Although methods and names for the techniques are not entirely consistent in the literature, I will provide some description of categories and techniques seem to be fairly popular. Vergne (2008) categorizes hard rock mining methods in two ways: bulk mining versus selective mining and the level of needed artificial support in underground open areas–none or minimal, substantial added support, and caving methods where the roof caving in is part of the process. Harraz (2010-2011, p.51) adds an additional category of short-hole or long-hole mining methods. The subcategories tend to depend on the design of the production openings and the direction the mining takes (Hartman and Mutmansky, 2002).

Bulk or unselective methods are typical with large deposits of low-grade ore, where all the ore is mined. Whereas in more expensive selective mining, high grade ores spread throughout the deposit are mined leaving the low grade ores in the ground. Harraz (2010-2011) indicates three common unselective methods in hard rock mining as block caving, sublevel caving, and vertical crater retreat.

Caving methods are unsupported. They require gravity and the ore bodies must be weak enough to cave in when the underneath supporting rock is removed. Subsidence at the surface must also be allowed, if the mine is shallow enough. If the ore body is gently dipped, block caving may be applied. The method starts near the bottom of the deposit with a blasted out undercut. With removal of the material in the undercut area, the ore above caves in. Drilling and blasting may be used if the material above is too strong to cave in on its own. Passages drilled between the undercut and a lower extraction area allow the ore to fall and be scooped up by load, haul, dump (LHD) trucks that transfer ore along drifts or underground tunnels. The trucks may be diesel or electric. In a space context, we expect they would be electric. In a shallow mine, the truck may take the ore to the surface. For deeper mines the ore may go to an underground crusher first or may be transported directly to the surface from a collection point by hoists or conveyors to be crushed. To maintain its integrity, the extraction level is typically reinforced. Mines using this technique include copper, copper-gold, iron, molybdenum (Minera, 2017).

If the deposit is minable by caving but has a steep dip, more expensive sublevel caving may be a preferred option. It starts near the top of the ore body with a cut below the first ore to be extracted. One reason it is more expensive is it requires blasting at each cut to cave in the rock above. Trucks remove the rock and ore from the cut as in block caving for further crushing before or after transport to the surface. Parallel cuts are made at various levels throughout the ore body. With proper sequencing more than one level of cut can be mined at the same time. Long wall as discussed above in soft rock mining is also a caving method (Hamrin, 1980).

The third bulk method suggested by Harraz (2010-2011), is vertical crater retreat. It is not a caving method, but as with vertical level caving it starts from the bottom up. A basic distinction between the two non-caving methods of underground mining is how much artificial support is needed. Vertical crater retreat (VCR) belongs to the supported methods since the rock is weak but subsidence is not allowed. In VCR, large diameter holes are drilled from a cut at the top of the ore panel to be blasted called a top cut or top sill to an undercut of the panel. The top sill and any other areas where needed are supported by various types of bolts and wire mesh. A panel may be the width of the ore and 9-15 meters deep and 20-90 meters high. The blast is from near the bottom of the blast hole and creates spherical downward facing craters. Enough ore is removed by remote controlled LHD trucks to allow a vertically higher charge to be set until the top sill is reached and all remaining ore is removed. The mined out panel is usually filled with tailings mixed with cement (Trotter, 1991).

Selective methods are used when the more valuable pockets are distributed throughout the rock. These ore pockets are mined leaving the less valuable material behind. These methods can be unsupported as in room and pillar (discussed above) and open stoping techniques with subvariants including stope and pillar, sublevel stoping, long hole stoping, and shrinkage stoping. Supported selective methods include cut and fill as well as bench and fill. Techniques may vary in the same mine across different areas and at different times as the characteristics of the deposits being mined change (Dutton, 2020; Harraz, 2010-2011; Hartman and Mutmansky, 2002).

In underground mines, stoping is the process for extracting ore from the surrounding rock by drilling and blasting. The surrounding rock must be strong enough to not cave in during this process. When non-ore waste rock is extracted with the ore, the share of dilution equals (waste rock)/(total material mined). This waste rock and mixed in earth material is called gangue. If some valuable ore is left in the formation, the recovery share equals (the ore that is mined)/(ore in the formation).

Open stoping is a non-supported technique (The Editors of Encyclopedia Britannica, n.d.-b). Two main differences in open stoping methods depend on whether the ore is removed from above (underhand) with the mining operation moving from top in a downward direction, or ore is removed from below (overhand) with the mining operation moving from the bottom in an upward direction. Room and pillar, discussed above, used for softer rock, is more often an underhand method (Buchan, 2012). Stope and pillar is similar to room and pillar but is more typical for harder rock and stopes are typically not as regular in shape as rooms. Stope and pillar is the most common underground hard rock mining technique (Hartman and Mutmansky, 2002).

Sublevel stoping is an overhand method that may be used when the ore has a steep dip but a fairly regular shape. Starting from the bottom sublevel, primary stopes are blasted, LHD trucks remove the ore and the emptied stopes are backfilled with tailings and concrete. Pillars are initially left between the stopes for support. These backfilled stops will become secondary stopes when the primary stopes are mined out. Mining tends to move upward, but different areas on more than one sublevel may be mined at the same time. In long hole open stoping, the blast holes are very long and may extend from 10 meters up to even 40 meters or more (Plc, n.d.). The entire hole is typically blasted at once, and the broken ore falls down to the draw point, where is it removed by remote controlled LHD. Shrinkage stoping works well in steeply dipped ore between strong rock walls. Broken ore is left to become support for the next layer of mining moving up. Since blasted ore takes up more space, enough ore is removed so there is room to continue mining. Once the area is all broken up all the remaining ore is removed. Videos for room and pillar, long hole, and sublevel stoping can be found at Epiroc Underground Mining and Tunneling (2019b), Hydro Power Equipment (2016), and (Epiroc Underground Mining and Tunneling, 2019c), respectively.

If the ore and surrounding rock require selective mining but the ore body and surrounding rock are too weak to support drilling and blasting, and caving is not allowed because of surface subsidence, artificially supported methods are used as you go along. If the ore is steeply dipped and irregular, cut and fill stoping may be used. In this overhand method, the ore is divided into horizontal slices. Starting with the bottom slice, the ore is blasted and removed by LHD truck. When the slice is mined, the sliced is immediately back filled with waste rock, mine tailings and maybe concrete. The filled slice then becomes the platform for the next slice up. If the ore body is wider, drift and fill may be employed. In this case, one narrower horizontal slice is cut and filled, before the operation drifts horizontally to mine another stope. The operation keeps drifting until the entire width of the horizontal slice has been mined out and filled. See Epiroc Underground Mining and Tunneling (2019a) for a video showing cut and fill.After the ore is broken, it is eventually transported to the surface. Vertical transportation of ore would typically be through a shaft with some kind of hoist, inclined transportation would typically be done by conveyor belt or truck, and horizontal transportation would be done by conveyor belt, truck or rail. The choices are made when the mine is designed and depend on things like the depth of the ore, the amount of overburden, the strength of the rock and ore, and the tonnage volume per day (Vergne, 2008, p.61). With continuous mining, often favored for coal, it might be dropped onto a conveyor belt that goes to the surface. With other methods, the ore may be taken by truck to a collection point where it may be taken to the surface or it may be crushed into smaller pieces before it is taken to the surface.

Before processing, the mined material, called run of the mine (ROM) ore consists of compounds that contain the valuable material and other worthless material called gangue. The goal of processing at the mine is to concentrate the ore separating the valuable compounds from the gangue waste. This processing is typically similar whether the ore is mined from the surface or underground. Ver09 suggests there are three stages to processing: comminution, which breaks the ore in finer pieces by crushing and grinding, beneficiation, which separates and concentrates the valuable ore from the gangue (separation and concentration, and if the valuable material contains more than one valuable component they may need to be further processed by smelting or refining. The mechanical process of breaking the run of mine ore further, may begin underground with a primary crushing (Multotec, n.d.). Crushing, often the first step, is typically a dry process with the material put under pressure between two hard surfaces to break it into smaller pieces. The surfaces may be pressed together as in jaw crushers or vibrating as in gyrator crushers. Typically, ore is crushed more than once, with successive crushing stages outputting smaller and smaller particles. Secondary and tertiary and later crushing stages are more often done with cone crushers in which rock passing the rock between large rotating cylinders A typical crusher reduction in particle size is 6 to 1 per crushing (EPA, n.d.; Schlitt, Callow, Kenyen, and Pizarro, 1992, p.2184-2249). See Talleres Felipe Verdés (2019) for videos illustrating 9 different crushers.

Between crushing stages, crushed ore may be classified by sorting material particles by size or weight to remove large debris for discard, larger rocks that need to be cycled back and recrushed, or smaller stones that can skip the next crushing stage. Classification of crushed ore is most likely done by static or vibrating screens (that classify by size) On softer ore, other types of crushers may rely on accelerating rock material to high velocities to get broken by hammers, by other rock, or upon impact (Schlitt et al., 1992, p.2184-2249). Once the rock size is small enough it is sent on to be ground into even finer particles, in the grinders. Crushers on the surface may be located in the mill, the building where the final two mine processes take place (grinding and separation), or crushers may be outside the mill and pass the crushed material on to the mill.

Grinding is more often a wet process and is the most energy intensive of the mining processes. It is also often done in stages until the particle size is small enough for beneficiation (separating and concentrating the ore and sending the gangue removed to be tailings). As with all mining and processing technologies, the choice of the grinder technology depends on the qualities of the material to be ground. Satyendra (2015) lists these qualities as "(i) hardness, (ii) brittleness, (iii) toughness, (iv) abrasiveness, (v) stickiness, (vi) softening and melting temperature, (vii) structure (e.g. close grained or cellular), (viii) specific gravity, (ix) free moisture content, (x) chemical stability, (xi) homogeneity, and (xii) purity." Tumbling grinders are typically cylindrical shells that rotate horizontally with the material to be ground inside. Such grinders that include a significant amount of added steel bars, steel balls, or porcelain pebbles to help grind the ore are called rod, ball, or pebble grinders. Tumbling grinders that only include the ore to be ground and run of the mine ore or primary ore are called autogenous. Semi-autogenous grinders tumble a combination of ore and some additional steel or porcelain material. Ball and the larger semi-autogenous grinders tend to be the most popular methods. Primary feedstock coming from older crushers may have practical diameters from 100-150 mm (4-6 inches). Feedstock particles into newer larger semi- and autogenous mills tend to have double those diameters. Ball mills may reduce particle size from 60 to 1 (Vergne, 2008, p.262). Autogenous mills are more suited to large installations, i.e. more than 50 tons per hour and have a power requirement ranging from 40 kW up to hundreds of kW (Peters, 1992, pp. 221-232).

Along with comminution, classification of particles by size is often needed to help direct particles in the grinding stages. This may be done as noted above by screening. Another common method is by hydrocyclone, if the feed is in the form of a slurry. Hydrocyclones may be used to separate particles by size, shape and specific gravity (Wills and Finch, 2016, pp. 203-204). As these versatile cone shaped devices spin, centrifugal forces typically push slower settling particles to the wall of the cyclone and heavier particles to fall through an outlet at the bottom. Particle sizes falling through the bottom exit can be controlled by the outlet design (Bradley, 2011).

Vergne (2008) indicates that mills are typically water intensive often requiring up to 3 tons of water for each ton of ore processed, which can be reduced to 1 ton of water per ton of ore in arid climates. Nevertheless, if the above water intensive methods are to be applied in space, water availability and the capability to recycle water will be an important parameter in making space mining decisions.

Once the particles are small enough, we are ready to complete the separating and concentration of particles into the valuable ore that the mine sells and the tailings that will be discarded. This process is often called beneficiation and is based on the different physical properties of the valuable and waste products. These differences include different surface properties, densities, electrical conductivity, magnetic properties, and optical characteristics (Wills and Finch, 2016).

Surface-mined coal from the Powder River Basin is usually simply sized and screened in preparation for market, whereas underground-mined coal and surface-mined coal from the Interior and Appalachian basins often requires a greater amount of processing (see below) to improve its marketability (National Research Council, 2007, p.57-79).

Removal of the mineral matter (or “ash”), which is largely noncombustible and may constitute up to 65 percent of the raw coal, increases the heating value of the coal on a mass basis. Although some combustible material is lost as part of the cleaning process, the removal of unwanted material reduces the mass and volume of coal for a given heating value, thereby reducing shipping costs as well as minimizing coal handling and ash management costs for the end user. Processing allows greater control over the “quality” of the coal—principally ash and moisture—which improves its consistency for end users, such as electricity generators or coke manufacturers. Improved and consistent quality increases the efficiency and availability of steam boilers and is particularly important for the quality of metallurgical coke. Physical processing can, to some extent, reduce sulfur and trace element contents, particularly on a heating value basis. However, coal cleaning is not practiced primarily for this purpose except for the metallurgical coal market.The most common separation method, which depends on the surface characteristics of the particles, is flotation (Vergne, 2008). Wills and Finch (2016) show it is a rather versatile method given the wider variety of feed particle sizes it can process as shown in figure 3.

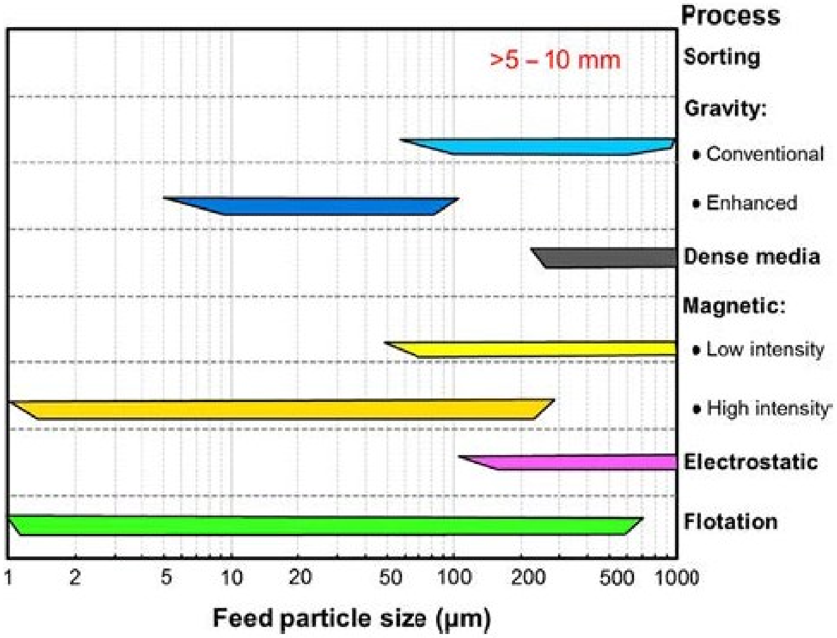


Figure 3: Separation applications depend on desired particle sizes

Source: Wills and Finch (2016, p.8)

Note: a millimeter mm is one thousandth of a meter, a micro meter (μm) is a millionth of a meter.

Flotation is especially favored with sulfide ores. The particles coming from the final grinding stage are added to a liquid (commonly water) along with one or more reagents or regulators. The resulting concoction is called a pulp. The regulators affect the surface of the different type particles in the pulp differently changing their affinity to water. Hydrophobic particles repel water, hydrophilic particles attract water. If the reagent is a depressant for a particle type, it makes the particle hydrophilic; if it is an activator, it makes the particle hydrophobic; if it is a dispersant, it helps keep the particles from coagulating, which would hinder the needed chemical reaction; if it is a pH modifier, it changes the pH balance of the pulp making it more alkaline (Wills and Finch, 2016, p.7, 280, 286). Regulators must be tailored to the particular ores being concentrated (Wills and Finch, 2016, p.280-286) indicate a number of regulators and their uses. (e.g. activators include copper ions and sodium sulfide; depressants include sodium cyanide, zinc sulfate, sulfur dioxide, and sodium hydrosulfide; dispersants include sodium silicate and some depressants also act as dispersants, pH balancers include lime and sodium carbonate.

When air is bubbled through the appropriate liquid mixture, the desired material attaches to the air bubble and floats to the surface to be skimmed off. Alternately, the gangue can be particles that rise and are siphoned off. Flotation methods are widely used to help concentrate ores for many mined materials including copper, lead, zinc, nickel, phosphate, and potash. If a flotation process is applied to coal it is called washing. Flotation has made commercial recovery possible from lower quality of ores and may be followed with other methods to increase the concentration further (Hartman, 1992, p.24-37; Schlitt et al., 1992, p.2184-2249).

Another popular method is gravity separation, which may rely on the Earth's natural gravity or simulated gravity by centrifugal force. Only concentration by hand is an older method. Hand sorting and simple gravity concentration in the form of panning and sluicing, mentioned above, is still used in very small scale unmechanized informal mining operations, called artisanal mining. The World Bank estimated there are around 100 million artisanal miners around the world. Such miners and other very small scale operators are thought to have produced a significant portion of the world's: sapphire's (80%), gold (20%), and diamonds (up to 20%) using such unmechanized method (Worldbank, 2013).

Gravity separation relies on differences in specific gravity, weight, size, and shape of particles, which determine how fast a particle passes through a viscous medium, typically air or water. It tends to work best for rich coarse ores (particle size down to 50 µm, see figure 3). It is low cost and can handle large quantities, but is not always the most accurate. Methods may have difficulty separating particles with small differences in specific gravity or separating for very small particle sizes (Kenyen, 1992). If ultrafine gangue particles called slimes with diameter less than 10 µm are present, they may need to be removed first for gravity separation for gravity separation to be effective (Wills and Finch, 2016, p.7).

We can add a number of other gravity concentrating methods from Wills and Finch (2016), chapters 10-11. Methods include jigs, spiral concentrators, shaking tables, pinched sluices and cones, fluidized bed concentrators and dense medium separation. Jigs like sluices, have been around for some time. They typically concentrate rather course particles from 3 – 10 mm. The basic operation is as follows. The simplest jig is a water filled open tank. The ore is placed on the jig bed usually composed of a screen. Pulsing water pushes the particles upward. As they settle, the particles with higher specific gravity fall to the bottom faster and are extracted and those with lower gravities are extracted at the top. Usually, but not always, the valued materials are the materials at the bottom (Michaud, 2016).

Spiral concentrators are newer having been introduced in 1943. They can process particles from 3 mm down to around 75 µm. They have seen their heaviest application in recovery of metals from mineral sands and recovering fine coal particles. In a spiral concentrator, the ore slurry passes through a sluice that is a tube that spirals down around a central collection pipe. Heavier particles travel slower and move to the inner part of the spiral to be drawn off into the collection pipe and lighter particles stay on the outer part of the spiral and move more quickly to the bottom to be drawn off. For higher capacity, dual or even triple spiral tubes may surround one collection pipe. They are often stacked to successively reprocess particles until the final grade of ore is accomplished (Gupta and Yan, 2006).For a video of a shaking table, see Royal Manufacturing (2020) Shaking tables are rectangular slanted tables with ridges (called riffles) along the long axis of the table. The riffles go part way down the table and are tapered. That is the riffles get successively longer as you move across the table away from where the feed enters. An ore slurry is fed across the table and additional wash water also crosses the table, while the table shakes along the long axes. As the slurry passes across the table, friction slows the velocity of the water closest to the table and the denser material gets caught between the ridges, while the lighter materials pass over the ridges and into the tailings trough. The more valuable dense materials pass down the ridges to be collected at the far end of the table. Additional collection points may be added to collect materials for recycle materials that may still contain valuable materials (JXSC, n.d.-b). Parameters that can be changed depending on the feedstock being processed include the slope and surface of the table, slurry density, slurry and wash water feed rates, and amplitude of the shaking. Common examples of minerals concentrated by such tables include tin, iron, tungsten, tantalum, mica, barium, titanium (Wills and Finch, 2016, p. 235).

Wills and Finch (2016, ch.10) discuss a number of centrifugal concentrators. Since these concentrators simulate gravity using centrifugal force, they might be helpful for space applications. Although designs vary, the central principle is to feed an ore slurry down into a round, cone shaped or cylindrical vessel that rotates at high speeds. As the vessel spins, slower heavier valuable particles are trapped in grooves in the vessel wall and lighter particles pass upward and out to be discarded. Some models can separate out particles down to 3 µm (Savona Equipment, 2018). A Knelson is one such concentrator. Greenwood, Langlois, and Waters (2013) show that a Knelson concentrator can be modified to also concentrate titanium using air instead of water as medium. But this dry process has a lower efficiency.

Fluidized bed separators can separate particles from 1 to 0.15 mm (MIningExclusive, 2011a). To do so, typically a feed slurry is fed down into the vessel, while a current of water is forced upward in the vessel.

The velocity of the water current should match the downward velocity of the finest descending particles. This causes a fluidized bed to form at the bottom and lighter waste to flow out the top. In a fluidized bed, solid particles behave as a liquid and the heavier valuable products can be removed from the bottom (Wills and Finch, 2016, ch.10).

Again, dry gravity based separation can be applied in fluidized bed separators using air as the medium instead of liquid. An initial important dry application was in U.S. coal preparation, with the maximum tonnage processed in the 1960s. Such pneumatic technologies tend to parallel the steps in wet processing. Pneumatic tables push the feed along a level porous bed with rifles that allowed air to continuously blow up through the bed and the feed with the densest particles accumulating at the top. Dry separation using tables, air jigs and other pneumatic devices and their operation are considered in Wills and Finch (2016, p 240-242).

Another straight forward and popular approach is dense medium separation (DMS). It is popularly called sink and float. The medium in this case has a specific gravity between that of the two materials being separated. The lighter material then floats up in the medium and can be removed from the top, and the heavier material sinks in the medium and can be removed from the bottom. The dense medium is typically recycled (Wills and Finch, 2016, Ch 11). Common solid materials to be added to water to create the dense medium are quartz (SiO_2), magnetite (Fe_3O_4), and ferrosilicon (FeSi) (Kenyen, 1992). DMS can be adapted for a wide range of particle sizes, but can also discern between particles that are quite close in specific gravity. As it can take quite large particles it may be used for precondition ores to reduce particle size for other processes. It is also used for beneficiation of coal, iron ore, and diamonds.

Dry modifications can typically be made to most such liquid processes if water is in short supply or water would damage the end produce (Wills and Finch, 2016, Ch 11). Dry processes are not used so often as there may be more problems relating to the control of dust and efficiency is especially denigrated for at small particle sizes. Such air based approaches tend to be less commonly employed, as undesirable attributes of air processing include: difficulties in dust containment, problems with separating fines or very small particles, and lower efficiency than similar water-based approaches. (Wills and Finch, 2016, p.235-237).

Leaching may be used in situ, but may also be used as concentration method at the surface. It is sometimes called solution mining in this context. If gold and silver are independent particles in the ore coming from the grinding mills and not in chemical solution, leaching tends to be the most popular separation method (Vergne, 2008). The ore is leached with a diluted alkaline solution of sodium cyanide that is made more alkaline by adding hydrated lime. The metals react and become compounds with the cyanide. Further chemical processing of the cyanide solution is used to separate the gold and silver from the cyanide. One such separation technique called carbon in columns reacts granular carbon with the solution and then a hot corrosive alkali is used. Then electricity or zinc dust is used to help recover the gold and silver (Manning and Kappes, 2016). Leaching may also be applied to old tailings with metal concentrates that were previously too low for commercial recovery (Manning and Kappes, 2016). This can allow recover of metals that react with cyanide including not only gold and silver but platinum group metals, iron, copper, and zinc. Although cyanide can be lethal, it is used in fairly low concentrates and is typically recycled Wills and Finch (2016, p.439) discuss some of the ways to process cyanide wastes from ore processing. If the gold and silver are not separate but are already trapped in compounds, flotation is often a more likely method for concentration (Vergne, 2008). For copper, the leaching agent or lixiviant depends on the ore. For copper oxides, sulfuric acid tends to be favored. For other types of copper ores, the process is more complicated usually involves and oxidant such as ferric iron (Schlitt, 1992).

All minerals react in some way to magnetic fields. They may be attracted (paramagnetic) or repelled (diamagnetic) along the line of magnetic force. These lines of force in a magnet go from north (negative) to south (positive). For some metals the reaction may be strong enough to allow separation of valuable ore using magnets. Iron, nickel, and cobalt are strongly paramagnetic (also referred to as ferromagnetic).

Some of their ores are ferromagnetic and can be separated by weak or low intensity magnets from gangue, some are just paramagnetic requiring stronger or high intensity magnets. Oxygen, tungsten, and aluminum are weakly paramagnetic and ores with them would more likely require high intensity magnets for separation Some products become paramagnetic at very low temperatures and are called super conductors (Baird, 2013). Although a number of elements and compounds are superconductors at normal atmospheric pressure, the temperatures needed are measured in Kelvin (0 Kelvin = -273.15 °C or -°F) and are extremely low. The elements with the highest transition temperature, the temperature below which they become super conductors, are niobium (9.22 °K, lead 7.26°K, and lanthanum 4.71°K) (Webba, Marsigliob, and Hirscha, 2015). Most forms of carbon are not superconductors but surprisingly some forms of carbon, nanotubes, have shown a transition temperature as high 15 °K (Superconductors, n.d.). Given the low temperatures in Space (averaging 3°K), this property might be used to help separate super conductors with transition temperatures warmer than 3 °K on very small objects that do not retain radiated heat.

Super conductivity was discovered in 1911. Much effort has been expended to understand such conductivity with the currently accepted theory not discovered until 1972 by Bardeen, Cooper and Schrieffer. They received the Nobel Prize in Physics for their theory of super conductivity. See (Slichter, 2007)for the history of these discoveries. Since then the search has been on for super conductors at higher temperatures. (Kostrzewa, Szczęśniak, Durajski, and Szczęśniak, 2020) report that in 2014 and 2015, hydrogen sulfide (H2S) and sulfur trihydride (H3S) were found to superconduct at very high pressures (around 1.5 million times normal earth atmospheric pressure): critical temperature around 150 °K (-123.15 °C, -189.7 °F) and 203 °K (-70.15 °C, -94.27 °F), respectively. In their research, they found somewhat better results for lanthanum decahydride (LaH10) critical temperature around 215 °K (-58.15 °C, -72.7 °F) at about 1.50 million times normal earth air pressure and 260 °K (-13.15 °C, 8.3 °F) at about 1.90 million times normal earth air pressure, respectively. (Snider et al., 2020) report even higher critical temperatures (considered to be room temperature) for a Carbon-Sulfur-Hydrogen system with critical temperature around 288 °K (15 °K, 59 °F) at around 2.64 million times normal earth air pressure. Thus, adding very high pressures increases the number of super conductors, but might be hard to achieve in Space.

Separation using magnetics principles requires an understanding of magnetic properties of materials being separated. Magnetic fields created by magnets have lines of force. With more lines of force per unit area, the higher the intensity of the field. In mineral processing, we can think of higher intensity magnets creating more lines of force. Separation of ferromagnetic materials usually require only low intensity magnets, whereas diamagnetic materials are more likely to require high intensity magnets. The intensity of the lines of force may change in the magnetic material as the distance from the magnet increases. This change in intensity is called the gradient. Magnetic material separation depends on the intensity, gradient and particle size of the feedstock (Wills and Finch, 2016, Ch 13).

Magnetic separation may be as simple as a suspended magnet over a conveyor belt during various stages of processing to lift out iron materials when they are not the desired material. It may also be used to separate out desired metallic ores. Magnetic separators may be wet or dry; use low, high or variable intensity magnets; and the magnets may be permanent or electromagnet. If wet, water is added to the feed. In a drum separator, ore is typically fed into a drum that revolves around an inner drum. The ore may be dry or for smaller particles it may be wet (Wills and Finch, 2016, Ch 13). The inner drum usually has a permanent magnet around part of the drum. As the material passes by the inner drum, the magnetic material passes along the inner wall following the drum, while the nonmagnetic material falls off near the bottom of the drum at a tailings collection point. The permanent magnet in the inner drum extends only a short ways beyond the tailing collection point. When the magnetic material gets beyond the magnet, it falls into its collection point (Outotec, 2013).

Two common types of dry magnetic separators are: cross belt and roll separators. A cross belt magnetic separator is a lift type of separator, the dry feed stock is typically passed in on a conveyor belt. A ridged cross belt above passes across and under a permanent magnet that lifts up the magnetic material as it passes under. The material is caught by the ridges on the cross belt and dropped into the collection point as the cross belt passes out from under the magnet to cycle back around. The non-magnetic material stays on the lower belt and passes on and is dropped off at its collection point (Shields Company, n.d.). A roll separator is typically a conveyor belt carrying the ore over a magnet. When the ore gets to the end of the belt, the nonmagnetic material falls off into its collection area. The magnetic material sticks to the belt until it passes beyond the magnet and then falls off into its collection area. In the above applications, electromagnets requiring electricity were often the more traditional choice for magnets but they have been largely replaced by the more newly developed rare Earth magnets (Wills and Finch, 2016, Ch 13).

The above low intensity methods can be used for separating courser particles of ferromagnetic and strongly paramagnetic materials. The induced roll is a flexible high intensity separator. It can separate more weakly paramagnetic materials and smaller particle sizes (2mm to 2μm) than the low intensity separators (Bunting, n.d.). The basic configuration is to have a rotating roller between two powerful electromagnets. The electromagnets induce the rotating roller to become an induced magnet. The dry feed enters the roller from above through a hopper or vibrating feeder (Holm-Denoma, 2021). As the ore passes down and around the roller, the non-magnetic material is discharged by centrifugal force and a divider into a collector. The magnetic material is carried along as it is attracted to the roller and some non-magnetic material maybe carried along as well. A second divider and centrifugal force collection point collects much of the remaining non-magnetic material with some of the magnetic material carried off as well. This material, called middlings, may be reprocessed to separate out more of the valued material. At the final divider and collection point the ore with the highest paramagnetic material is taken off. Grooves on the roller create a high magnetic gradient across the roller, which help move particles across the roller and improves the separation efficiency. These machines are quite flexible as the magnetic intensity and roller speed can be varied and they can be adapted for different particle sizes. This flexibility allows adaptation to a variety of mineral compositions (Redditch, 2018, 2020b) (Fears, 2019; Magnetsource, n.d.).

If the weak paramagnetic particles get smaller than 45 μm, the dry induced roll does not work well, but another option can take on the job. The first wet high-intensity magnetic separator (WHIMS) was patented by Jones in 1963 (Ribeiro and Ribeiro, 2015). The advantages of the WHIMS are that a wet slurry works better for very small particles, dust is less of a problem, and the ore does not need to be dried before separation. The most basic principle difference for the Jones WHIMS is to introduce highly magnetic material between the two electromagnets. This ferro magnetic material is called a matrix and has to allow the ore particles to pass through. The original matrix consisted of grooved parallel steel plates. The separation of the plates or nonhomogeneities in the matrix creates high gradients. When the slurry passes through the high intensity high gradient matrix, the magnetic particles become magnets and fine particles start to aggregate and stick to the matrix. Nonmagnetic particles fall through to a collection point. Wash water passing through helps wash out any remaining non-magnetic particles from the matrix. Removing the magnetic field from the matrix and adding wash water removes the magnetic particles. Small scale operations may be batched (Redditch, 2021).

Large scale operation WHIMS are typically conducted on continuous vertical or horizontal rotating carrousel or rings with compartments around the perimeter that hold the matrix material. Slurry is fed into each matrix compartment as it passes. As each successive slurry compartment approaches a magnetic pole, water is flushed into it. As the watered slurry rotates past the magnets, magnetic particle stick to the matrix and each other and nonmagnetic materials fall into their collection point. As each compartment continues out of the magnets range, it is again flushed with water to wash out the magnetic materials into their collection point (MIningExclusive, 2011b). The design must be able to aggregate very fine particles without trapping non-magnetic material in these small magnetic aggregations (Composite Nanoadsorbents, 2019).

As the matrix took up quite a bit of space in the original WHIMS matrix, some newer improvements and variants include using pulsing water instead of gravity fed water to increase separation efficiency; matrix variants that take up less process space including steel rods, sheets of steel grating and steel wool; and changing the magnet design to not be seated outside the ring but to encircle the processing tube putting it closer to the feed and generating higher magnetic intensity (Wills and Finch, 2016, Ch 13).

Processes can be used and combined in sequence to process ever finer particles and more concentrated ores. Models are also designed for these and other separators to use rare earth permanent magnets made of neodymium iron and boron (Eriez, 2015; Wills and Finch, 2016) (Metso, n.d.; TV, 2021). Super conducting magnets can be used if particles are very fine with low magnetic attraction requiring a magnet that can produce a very high magnetic intensity (QuantumDesignUSA, 2013). However, recall that these materials are only super conductors below their critical temperature. Such magnets are typically made from niobium-titanium (NbTi, critical temperature around 10 degrees Kelvin) and sometimes from niobium tin (Nb3Sn, critical temperature 18 degrees Kelvin) or a combination of both compounds. In construction, the super conducting material is made into very fine wires and embedded in solid copper. The magnets are kept cryogenically cold using liquid helium. Even though they require super cold temperatures, they require less total electricity than traditional electromagnets (Coyne, 2009; Fundamental Biomaterials: Metals, 2018; Hyperphysics, n.d.).

The last mineral ore concentration techniques, I consider here are electrostatic processing, which are based on how conductive a material is. Some materials are good conductors and allow electrons to easily pass through them (e.g. silver, copper, gold, steel, sea water). Others are insulators and do not allow electrons to easily pass (rubber, glass, oil, diamond, and dry wood) (Helmenstine, 2019). The first step in electrical separation is to create a charge on the particles followed by a compatible separation technique. Three common ways to do this are ion bombardment, conductive induction, and frictional charging, often called tribocharging. An ion is an electrically charged particle in which the protons do not equal the number of electrons. With more electrons, it is a negative ion and with more protons, it is a positive ion. In ion bombardment, a high-voltage is applied between 2 electrodes (or conductors) knocking off electrons creating positively ionized gas between them. When the mineral particles pass through the gas, they become positively ionized. Often one of the electrodes is a revolving stainless steel or titanium roller that is attached to a ground. A grounded surface with lower charge density will absorb electrons from a nearby negatively charged particle and will pass electrons to a nearby positively charged particle (Physicsclassroom, n.d.). As the particles move around and down the roller, highly conductive materials lose their charge faster and are thrown off the roll by centrifugal force, the remaining positively charged insulators stay attracted to the roller longer until they lose enough charge to drop into their collection point. Applications of this popular process include heavy mineral sands and coal washing (Redditch, 2020a; Wills and Finch, 2016, Ch 13).

Conductive induction uses a slightly different method. Every charged particle has an electrical field around it. In this method, an electrode is given a negative charge. When the particles to be separated come into the electric field near the electrode, they become polarized. They don't become charged, but rather the electrons circling the nucleus, shift a bit. Electrons shift away from the negative electrode leaving the side of the particle nearest the electrode with a positive charge and the area farthest away with a negative charge (Britannica, n.d.-b). As the particles pass over a grounded surface across from the electrode, typically a plate or a roller, the conductors lose electrons to the grounded device and become positively charged. With this positive charge, conductors are attracted towards the negative electrode where they can be removed. The less reactive non-conductors remain neutral and are pulled down by gravity (Kelly, 2003; Wills and Finch, 2016, Ch 13).The third way to create a charge on a particle is to use friction. By rubbing particles together, electrons may move from one particle to the other creating a positive charge on the material that loses electrons and a negative charge on the particle that gains electrons (Classroom, 2021). Tribochargers feed in the particles so that contact creates such charged particles. The charged particles are often allowed to free fall by two oppositely charged electrodes, which divert the particles into their appropriate collection bin. Some new designs move the charged particle by belts. This collection process can work even if particles do not change the sign of their charge but just change the degree of charge on the particles. Particles may be pretreated by cleaning, using chemicals, applying heat, changing humidity or adding impurities to their surfaces to enhance charge differences and create better separation (Wills and Finch, 2016, Ch 13). An advantage of this method is that it can also be applied to the separation of non-conductive materials with commercial examples including the separations of calcite from quarts, feldspar from quartz, and coal from ash (Mirkowska, Kratzer, Teichert, and Flachberger, 2016).

For all the wet processes, the concentrated ore typically needs to be dried or dewatered and sometimes tailings are dewatered as well. Moreover, some dewatering may take place during the grinding and milling stages. Wills and Finch (2016, p.411) classify dewatering into three processes, which are often used in combination: sedimentation, filtration, and thermal drying. Typically, the process starts with sedimentation in which gravity or centrifugal force pulls solids out of the concentrated slurry. Sedimentation, also called thickening, has the widest use. This process works better, the denser the solids and tends to take out up to 80% of the liquid leaving a slurry that is 55%-65% ore. The thickened pulp may then be filtered so that the concentrate becomes 80-90% solid and thermal drying may concentrate further to 95% solid.

If the particles in the original slurry are very fine, they may settle very slowly. In such a case, the particles may be agglomerated into larger particles by adding reagents. Such processes include coagulation and flocculation depending on the action of the reagent. Coagulants alter the charge on fine particles allowing them to agglomerate, while flocculants are long-chain polymers that help stick particles together. If more water needs to be removed after sedimentation, filtering may be applied. Slurry may be agitated to feed evenly along the filter, and the filter may be under pressure or in a vacuum. Filters need to be porous, and they made from a variety of materials with cotton being a common choice. Processes include both batch and continuous processing with configurations including rotating drums, discs, belts, and pans (Wills and Finch, 2016, Ch 15).

The last step before shipment of the mineral may include thermal drying to get to the condensed ore down to 5% moisture. Low moisture means lower transport costs, reduced storage requirements, and allows for more recycling of water. It may also mean less fouling and better product flow in downstream processing, but keeping some moisture is desired for dust control (Capitaine and Carlson, n.d.). As with most mineral processing activities, there is a variety of equipment and process choices depending on the materials being handled and the equipment vender chosen. Rotating drum driers seem to be the most common thermal mineral driers. The rotating cylinder is inclined to allow the ore to pass through and hot air either inside the cylinder or hot air or steam outside the cylinder heats the material that is being dried (JXSC, n.d.-a, Ch 15; Wills and Finch, 2016, ch.15). Heat may be generated with coal or natural gas and recent work has been looking into concentrated solar for mineral drying (Nathan, 2019).

Wu, Hu, Lee, Mujumdar, and Li (2010, Table 3) list a variety of mineral drying techniques with applications including hearth drying for ores of zinc, lead, copper; grate drying relating to iron, copper, and chromium; fluidized bed drying for titanium oxide, zirconium silicate, and coal; and flash drying for very fine particles.

Although some materials (e.g. gravel, sand, diamonds, coal) may not need more processing after they leave the mine, in many cases the mine only concentrates the ore containing the desired materials. Those elements that are chemically bound to other elements and need further separation after concentration are sent off to refineries or smelters to extract the desired product. For example, unless they are the noble metals (ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), platinum (Pt), silver

(Ag) and gold (Au) and do not react easily with other elements) most metals ores are oxides, sulfides, or silicates (Chemistry LibreTexts, 2021). The concentrated ores from the mines are typically sent off to smelters to separate and extract the desired products. The final extraction process will typically be the same no matter where the ore is mined from. I will come back to this extraction process after I consider two more earthly sources of minerals – the ocean and the air.

Ocean mining is another area where we may learn a few lessons on processing in a harsh environment as well as learn some lessons on international space mining regulations. Eventually minerals from the ocean may also be a competitor for space mining for earth return. Seawater can be mined and currently significant amounts of magnesium and salt (NaCl) are mined from seawater along with lesser amounts of a few other minerals. Fresh water is also being recovered by desalinating sea water. Concentrating and extracting minerals from solution may prove to have some space applications, Hartman and Mutmansky (2002, p. 480-488) indicate three potential areas where we derive minerals from on or beneath the sea floor: unconsolidated or nonsolid minerals from the continental shelf, consolidated or solid minerals from the continental shelf, or deep water deposits including sulfides near hydrothermal or hot water vents, polymetallic nodules, and cobalt crusts. I will briefly consider the sources of these minerals and mining methods that might apply.

The source of minerals in seawater and in unconsolidated minerals on the seabed (gravel, sand, clay and silt, all of which may contain traces of metals) are typically weathering and erosion on land washed out to sea by rivers, melting glaciers, or the settling of atmospheric dust. Some may have formed on land during ice ages and only later became sea bed deposits as ice melted and the sea bed rose. Consolidated or solid minerals may have been created by undersea volcanic activities as happened on the land; they may be extensions of land deposits created long ago in marine environments such as for phosphate deposits (U.S. Congress, 1987). Undersea oil and gas deposits also were typically created by organic compounds in marine environments that were buried under pressure for long periods of time.

Deepwater metallic nodules (also called manganese modules) are typically composed of manganese and iron oxide and other metals and appear to be quite abundant (Hein, Koschinsky, and Kuhn, 2020). They are thought to have been created over millions of years by chemical reactions on metals precipitated out of seawater or out of water in bed sediments (Kuhn, Wegorzewski, Rühlemann, and Vink, 2017). Cobalt crusts are hard layers containing metallic material near undersea volcanoes. The volcanic sources metals in them have also precipitated out the seawater over millions of years. They contain similar metals to the manganese nodules but tend to have higher concentrations of iron, cobalt, REEs, and lead but lower concentrations of manganese, nickel, copper, and zinc (World Ocean Review, 2014a). On the sea floor, massive sulfide deposits form near hot vents at active undersea volcanos and along tectonic plate boundaries. Cold sea water passing down through sediments near such vents is heated. As the heated water rises to the sea floor, it carries sulfides that get deposited on the floor. Favorable conditions must exist for thousands of years for deposits to form. These sulfides contain significant concentrations of copper, zinc, gold, and silver but are significantly smaller mineral deposits than the more abundantly endowed nodules and crusts (World Ocean Review, 2014b).

So what can we learn from desalinated water and the potential for using its brine. Currently desalinated water accounts for only 1% of global use of fresh water (Fountain, 2019), but that is likely to increase as we move forward. The most common methods for commercial desalinization are multi flash distillation and reverse osmosis (Water Science School, 2019). Multiflash distillation (MFD) is an older process which brings in seawater, pressurizes it, brings it almost to a boil and then reduces the pressure in successive stages to create fresh water vapor. The impurities are left in a brine and the vapor is condensed by the new inflows of sea water (Bragg-Sitton, 2015).

Reverse osmosis (RO), newer, less energy intensive, and now the more common global method for desalinization, has been replacing (MFD). In RO, seawater is forces through a membrane that allows the smaller water molecules to pass through but not the salt and other impurities left behind in brine (Sdcwa, 2022). Given the likely scarcity of fresh water in Space and the need to recycle water, purification techniques are needed in Space. Although not as water frugal as in the science fiction novel Dune (Herbert, 1965), where even the moisture from dead bodies was recycled, NASA has been reprocessing astronaut urine and humidity from cabin air in Space since about 2009. Urine is first centrifuged to extract the vapor. The vapor is distilled, mixed with other waste water captured from cabin air, filtered through absorbent materials similar to processes on Earth, heated, injected with oxygen to oxidize remaining contaminants for removal, and treated with iodine (Anderson, 2020; Sauser, 2008). The ISS uses heat exchangers to control the humidity. As air passes through the heat exchangers, it gets cooler. The water in the air condenses (Lets Talk Science, 2019). For a discussion of other membrane based filration desalinization techniques and their properties including microfiltration, ultrafiltration, and nanofiltration, see Shon, Phuntsho, Chaudhary, Vigneswaran, and Cho (2013).

Currently the high salinity brine waste from desalination is injected back into the sea. However, this brine could also be mined for the salt and minerals it contains, and those methods may eventually have space applications as well. Although not so nearby, there is evidence that some of the moons in our solar system (e.g. Jupiter's Europa and Saturn's Enceladus) have salty liquids under the surface (NOAA, 2022). Loganathan, Naidu, and Vigneswaran (2007) investigate 4 methods for mining concentrated brine from desalination operations. They are (1) solar or vacuum evaporation, (2) electro-dialysis (ED), (3) membrane distillation/membrane distillation crystallization (MD/MDC), and (4) adsorption/desorption/crystallization (ADC).

Solar evaporation to produce salt and other minerals has been used for centuries with successive pans precipitating out different minerals with $NaCl$ coming out in the last pan. This method takes quite a lot of surface area and time, and it is not clear how it would work in Space. Adding heat can speed up the process but takes a lot of energy. Adding a vacuum means the water would boil at lower temperature and would lower the energy cost of added heat (Buschvacuum, 2017). Concentration of brines might be further enhance using wind-aided evaporation (WAIV). This involves spraying the brine on vertical structures lined up to allow the passage of wind to help evaporate the water (Gilron, Ramon, Assaf, and Kedem, 2019).

American Membrane Technology Association (n.d.) describes how membrane desalinization works. Salt in water breaks into ions or charged particles. Positively charged particles are called cations, and negatively charges particles are called anions. If they are monovalent, they have one less or one more electron than proton. If they are bivalent, they have two less or two more electrons than protons. To remove these ions, electro-dialysis uses a series of ion selection membranes in an electric field. The ions are moved by the electric field. The membranes permeable to positive ions, filter out negative ions and the ones permeable to negative ions filter out positive ions. The concentrated ions need further processing to capture the desired materials from them, as ED separates positive from negative ions, but ED has difficulty distinguishing between ions of the same charge. Although there has been research success with membranes that will separate monovalent from divalent ions with the same charge. Duxbury (2022) indicates the most abundant ions removed from Earth seawater with their valence charges as superscripts are chloride (Cl^-), sodium (Na^+), sulfate (SO^{2-}), magnesium (Mg^{2+}), calcium (Ca^{2+}), and potassium (K^+). Most of these have already been commercially extracted from sea water but the mining of brine is only in the research stage. As technology improves the mining of lower concentrate materials such as lithium and other metals may have space applications as well (Sharkh et al., 2022).

Membrane distillation is a combination of heat or distillation and membrane selection. Fluid streams come out of the distillation units at different temperatures and selective membranes separate the clean water from the waste stream. The advantages of this combined process over distillation only is separation at lower temperatures requiring less energy with increased potential for using renewable energy sources and a more concentrated waste stream that is more easily crystalized. The crystallization process has seen some progress in separating out for two salts $NaCl$ and $MgSO_4$ with the promise of separation of other materials. Challenges to this technology include membrane fouling from calcium deposits (Loganathan, Naidu, and Vigneswaran, 2017).

Crystallization to precipitate out minerals requires very high concentrations of the material. This may not be possible for many of the metals that exist at very low concentrations even in the desalinization brine. Loganathan et al. (2017) discusses adsorption/desorption which may concentrate minerals enough so they will crystalize. Adsorption is the process in which a solid (the adsorbent) holds a thin layer of a gas or liquid on its surface and desorption is the release of the film. In this process, the brine is brought in contact with high capacity selective absorbents for the desired material sometimes for weeks or months. In desorption, the absorbent may be regenerated or discarded and the desired material is contained in a concentrated solution that is subsequently crystallized for recovery. The desorption process used depends on the bond between the mineral and may be based on chemical, thermal, and ionic procedures. The most studied elements for ADC from sea water and desalination brine are lithium (Li), uranium (U), strontium (Sr), and rubellium (Rb)(Loganathan et al., 2017). All four of these could have space applications (Royal Society of Chemistry, n.d.-a, n.d.-b, n.d.-c, n.d.-d).

Further work is being conducted to more economically remove lithium from sea water including better membranes to filter out lithium and more efficient use of sunlight to evaporate water from brine (Campbell, 2016; 2022; King Abdullah University of Science and Technology, 2021). Better membrane filtering as well as cheaper lithium batteries are likely to have ramifications on space travel and recovering resources.

Moving now to the ocean bed and beneath it, the continental shelf is the shallow water portion that is adjacent to the land and extends to the continental break. The bed is gently sloping with water depths typically less than 200 meters until the break where the seabed becomes steeper and water depths increase more rapidly. It averages about 65 km from land but varies from less than a km to more than 1200 km. The International Law of the Sea negotiated in 1982 and operational since 1994 gives resource rights out to 370 km (200 miles) from shore to the adjacent country. If their continental shelf actually extends further than that, the country can apply for rights further out (National Geography; The Editors of Encyclopedia Britannica, 2022). These areas are designated as special economic zones (EEZ). Bilateral and multilateral negotiations are undertaken in places of overlapping jurisdictions. Outside these zones is international waters.

The Law of the Sea authorizes their International Seabed Authority (ISA) to oversee the activities related to mineral resources in international waters to the benefit all of humankind. ISA has issued 15 year exploration licenses to 22 countries since 2010 (ISA, n.d.). Exploration targets include polymetallic nodules, poly metallic sulfides, and cobalt rich feral manganese crusts. No exploitation contracts are yet to be issued, but ISA is working on exploitation regulations. As Space is a commons similar to international waters, the International Law of the Sea in 1982, the ISA and its subsequent activities might eventually serve as a starting point for furthering international agreements on space mining.

Almost all current mining is in shallow waters in the EEZs and includes sand, gravel, diamonds, and tin. Such mining is typically from nonconsolidated deposits (mineral sands) on the ocean floor in water less than 100 meters deep. Such mineral sands are typically recovered by dredging and the ore is concentrated on land as discussed above. Occasionally, consolidate deposits are extensions of land deposits and are mined from under the sea bed. They are usually mined using traditional underground mining techniques with the mine entrance on land (e.g. potash mining currently being mined in the British EEZ (NewsInWorldNow, 2013) and coal mining in Ellington colliery in England now closed (World Wide Meta Museum, n.d.).

However, interest in deep sea mining has been around for decades. It was brought up in the 1960s as an almost limitless source of manganese (Thompson, Miller, Currie, Johnston, and Santillo, 2018). In the 1980s, millions of dollars were spent by U.S. investors to prospect for deep sea minerals but the results were not deemed profitable and those efforts were abandoned. However, interest has remained and research groups and mining interests have continued to develop equipment (often robotic) for deep water undersea research and mining, all of which might have Space applications (Discovering Hydrothermal Vents, n.d.).

Hartman and Mutmansky (2002, p.482-484) discuss a generic ocean mining system includes a working platform, some way to move the ore to the surface, and seafloor equipment to excavate the ore. They identify some of the suggestions made for each of these categories. Woods Hole Oceanographic Institution (n.d.) indicates that such equipment includes "specialized dredgers, pumps, crawlers, drills, platforms, cutters and corers". Recently interest seems to be reviving. The Japan Oil, Gas, and Metals corporation (JOGMEC) has collaborated with industry, academia and Japan's Ministry of Economy, Trade and Industry (MITI) to recover some deep water minerals in Japan's EEZ. They have come from polymetallic sulfides near inactive hydrothermal vents (recovered in 2017) and from cobalt rich crust (more than ½ metric ton recovered in 2020). Both recoveries were in depths less than 2400 meters. Metals extracted include cobalt, nickel, copper, and zinc (Kyodo, 2017) (Jogmec, 2020) (Carver et al., 2020) (Japan, 2017). Jogmec (2020) indicates their method for sulfide recovery as follows. A controlled crust excavation machine moved across the sea floor on crawler tracks, while its cutting head broke up the crust. The resulting slurry was pumped to a waiting ship on the surface. Some seawater was separated out and the remaining ore was transported to land for further processing.

Japan has also discovered large reserves of rare-earth minerals in deep sea muds in their EEZ at a depth or around 6000 meters below sea level (Nature Research Custom, n.d.). Challenges of continuously mining such a deposit is how to pump the muds to surface. This will involve developing pipes, pumps, valves, subsea sensors and control modules that can operate effectively at depth and a subsea factory that turns the mud into a slurry that can be pumped to the surface (Kang and Liu, 2021).

Although we typically do not think of removing gases from the atmosphere as mining, we currently do have commercial operations to extract gases from the atmosphere including argon, nitrogen, and oxygen (McKelvey, 1986). Learning (2017) shows us how this is done. First, dust is filtered out of the air. The air is then liquefied by cooling it to -200 degrees centigrade (°C). As it is cooled, water vapor is filtered out. When CO2 freezes at -79 °C, it is removed. Next oxygen liquefies at -183 °C, argon liquefies at -186 °C, and nitrogen liquefies at -196 °C. This liquid mix of elements is then fractionated or distilled (cryogenic distillation) to separate the gases. The gas mix is then gradually heated from -200 °C. When we reach each gas's vaporization temperature, the gas boils off and is collected. This same method can be applied to the separation of other gases including helium and hydrogen. It has also been applied to the removal of CO2 from natural gas.

Although the moon and NEA do not have atmospheres, we might want to harvest solar dust. Furthermore space objects further afield do have some atmosphere (e.g. Venus, Mars, Mars' moon Titon, Saturn, Uranus, and Neptune (Pielke, 2022). They may well have applications in Space to extract materials for commercial use or to change climates as for CO2 removal. CO2 Capture Project (2008) indicates three methods for removing CO2 from a gas; using sorbents and solvents, using membranes, or cryogenic distillation as previous discussed. With sorbents the gas containing the CO2 is put in contact with the sorbent. The CO2 binds with the sorbent either on the surface, in a process called adsorbing, or is dissolved or dispersed throughout the sorbent also referred to as solvent in a process called absorbing. The process may be started or enhanced by adding heat. The CO2 and sorbent are then separated and the sorbent may be recycled or discarded. The separation process often requires a significant amount of energy. Amines are commonly used as solvents for CO2 capture. Zeolite or carbon can be used as an adsorbent for CO2.

With membrane separation, the gas containing CO2 is forced through the membrane by pressure. The collection is based on different sized molecules passing through the membrane at different rates. Membranes for CO2 capture may include those based on porous inorganic material, palladium, polymers, or zeolites. As membranes still are not able to get a high level of separation, they may require multiple stages with varying membranes. Membranes have yet to see large scale commercial application, but a considerable amount of research has been conducted to investigate the best membranes to do the job both for capturing CO2 from power plants and from the air. Fujikawa, Selyanchyn, and Kunitake (2020) consider state of the art of CO2 direct air capture. They conclude that pressure, membrane selectivity for CO2, CO2 concentration of the feed, required concentration of the CO2 captured stream and the permeability of the membrane per unit of thickness are all important attributes for successful membrane air capture of CO2. Although not yet ready for large scale use, they conclude it may be suitable for special small scale applications such as reducing CO2 concentrations in poorly ventilated space. Its advantages include the lowest energy use of the common capture methods, not requiring any chemical, and easy scalability for small applications in many locations might make it an appealing method for space applications. They found a thin film composite membrane with layers made of low-cost polymers to be promising.

Returning to mine processing, if the valued material is still trapped in the concentrated ore at the mine, extraction is needed. Such final extractive facilities are more often done offsite and may be contracted to another company. When the valued material is metallic, the extractive techniques are typically metallurgical processes. Extractive metallurgy uses four categories of extracting depending on whether they require heat (pyrometallurgy), dissolutions of the ore in water forming aqueous solutions (hydrometallurgy), electrolysis on salt solutions (electrometallurgy), or the use of halogens (halide metallurgy).

Pyrometallurgy is an old but popular methodology using heat (often at very high temperatures) to extract and purify metals. These temperatures may be applied to primary sources from metal ore or secondary materials from recycling of end-of life products. In addition to the processes for primary ore, recycled material may require additional processing to remove impurities and alloying materials. (Vignes, 2011a).

Many metals come in ores that are oxides (e.g. tin (Sn), iron (Fe), Manganese (Mn), chromium (Cr), aluminum (Al), nickel (Ni) or sulfides (e.g. copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), cadmium (Cd), and molybdenum (Mb). Two important operations in pyrometallurgy are smelting and roasting involving the chemical operations: reduction (gaining electrons) and oxidation (losing electrons) (Vignes, 2011c).

The reduction of oxides is the most important process in extractive metallurgy and is often done by pyrometallurgical processes. Smelting is one such pyrometallurgical process. The metal oxide is heated above the metals melting point in the presence of a reducing agent such as carbon. The oxygen lets go of the metal and combines with the carbon to produce carbon dioxide and carbon monoxide. A flux is also added to remove impurities. For example, in a blast furnace making pig iron, the flux is typically limestone. Other metals that are smelted include copper, zinc, tin and lead. Smelting removes the metal from the ore. Refining is the process to further remove small amounts of remaining impurity from separated metals and is usually pyrometallurgical. If refining is needed, it usually happens before the liquid metal is cast or poured in molds to solidify or converted into metal powder. Roasting heats the ore usually in the presence of an oxidizing agent to convert a sulfide to an oxide. The removed sulfide material is called a matte. Sulfur may be recovered from the matt and sold separately or the matte solution may be used for the recovery of other metals. The resulting metal oxide can be further processed by reduction to separate out the metal. (Sravan8, 2017; The Editors of Encyclopedia Britannica, 2016, 2017; Vignes, 2011a).

Alternately some metals will be removed using aqueous solutions typically at much lower temperatures but sometimes at higher pressures. These processes called hydrometallurgy include leaching, precipitation, and solvent extraction (Vignes, 2011b). With leaching, the ore is dissolved in an aqueous solution to form salt. Subsequently the metal is separated out. Common leaching solutions may be acidic (sulfuric or hydrochloric) as for zinc oxide or basic (caustic soda or ammonia) as for aluminum hydroxide and copper oxide. Sulfides may be leached first to oxidize them, before resultant products are dissolved for separation. Precipitation is the process where the metal or its oxide comes out of the solution. It may be the final stage of the leaching process. Solvent extraction is another means to separate out the metal. In the process a metal compound transfers from one solvent to another for easier separation (Wright, 2016) (e.g. from an acid solution to an oil based solution).

Electrical procedures are called electrometallurgy and use electrolysis for separation of metal from its ore called winning or it may be used to purify a metal called refining. With electrolysis, an electric current passes through a substance to cause it to lose or gain electrons. The process may start with an aqueous solution as from a leaching process or a molten salt as an electrolyte. When a direct current is passed from the anode to the cathode, the positive metal ions in the electrolyte are attracted to the cathode. Metals separated with an aqueous salt solution include copper, nickel, lead, and tin. Metals separated with a molten salt solution include aluminum and magnesium (Perez, 2004; The Editors of Encyclopedia Britannica, 2020; Vignes, 2011b).The last extractive mentioned here is to use halides. Where a halide is a compound that contains an element from the halogen group (e.g. chlorine, fluorine, iodine) and one other element. Halides may be used to reduce some of oxides of the more reactive metals such as titanium, zirconium, magnesium and aluminum. These oxides are not easily reduced into very pure forms because of their strong affinity for oxygen. The process developed is to convert the oxide into a halide with heat usually required for reaction (Vignes, 2011a). The halide is then reduced to separate out the metal. If the halogen is chlorine the reducing agent for some metals (e.g. tungsten and molybdenum) is hydrogen and for others (titanium and zirconium) reduction processes have been developed using magnesium, sodium, or calcium. While reduction processes for uranium tetrafluoride (UF4) have been developed using calcium magnesium.

Metal mining and processing has a long history on Earth beginning with the Bronze Age and even before thousands of years ago. Since then technology has continued to evolve into a great many complicated processes. Human ingenuity and perseverance has solved problem after to solve problem including finding and recovering new elements and recovering both old and new materials at lower and lower concentrations. Anderson et al. (2014) contain summaries of numerous in mineral processing and extraction over the last century.

If and when we begin to mine Space, we will surely build on and modify all the technology available to us. Many such processes require large amounts of water and gravity. They are typically capital and energy intensive processes with large economies of scale. A number of processes have already been applied at miniscule scale on the International Space Station, the Moon, Mars, some asteroids, and a comet. The big question is how can we do this collection and processing at scale in a harsh space environment and do it at commercially successful levels.

6. The Role for Miners and Machines in Space

From the first miner, who may have picked up a shiny rock and figured out how to extract a valuable material from it, capital and technology have become increasingly important. This importance seems likely to continue as mining techniques on Earth continue to evolve. Mining Technology (2020) suggests ten technologies that could be game changers for mining on Earth. Many of them will likely have applications in Space as well. Their first suggestion is the increased use of robotics. The earliest mention of robots in mining I have found was the use of robots for mine mapping in 2003 (https://www.azomining.com/Article.aspx?ArticleID=1499). In 2012, Hinton and others developed an improved visual recognition system base on deep learning. Their artificial intelligence (AI) system uses deep learning. By showing their robotic devices huge numbers of photographs, the devices can learn to recognize numerous objects they encounter (https://www.aventine.org/robotics/history-of-robotics). With such AI improvements, robots have been making inroads in mining and can perform a variety of mining tasks including mine mapping, ore sampling, drilling and blasting to loosen ore, loading and transporting, roof re-enforcement, and miner rescue. (Mining Technology, 2020).

As with many aspects of our current lives, (Mining Technology, 2020) suggests the internet of things (IoT) will likely increase in mining. This real time networking of miners and machines will increasingly allow mining operations all along the supply chain to be coordinated and automated to flow smoothly and continuously with fewer miners at the helm. Hopefully the dirty and dangerous jobs can be taken over by the machines. Some of their other suggestions for change are related to these type of increases in networking and automation including 3D laser imaging for mine exploration, trouble shooting, automated drilling and blasting with remote observation and guidance of activities in the mine. Autonomous haulage in mining was first employed in Australia in 2008 and has since been gaining traction. Remote sites for mining operational control and monitoring were introduced by Rio Tinto beginning in Australia in 2010. In 2014, a newer center in Brisbane was able to monitor their operations in Australia as well as Mongolia and the U.S. It seems pretty clear that remote control will be a prominent fixture in Space mining as well.

A few other technology improvements noted in (Mining Technology, 2020) include improved air-borne gravity gradiometers giving more precise information for mineral exploration. Such equipment might be applicable for mining on bodies that are large enough for discernible gravity. New equipment that can bore out tunnels faster and in harder materials seem likely candidates for space applications. New radio frequency plasma techniques have been developed recently that heat ores to extremely high temperatures, 8,000-12,000 ° C (9032 – 21632 ° F), with the potential of dramatically increasing the recovery of precious metals such as gold and platinum. Recall that a plasma is material at such a high temperature that many electrons are released from molecules leaving a significant portion of ionized particles in the superheated material. If we can muster the energy in Space to implement this technology it could have interesting repercussions down below, as precious metals from Space may have the potential to compete in markets on Earth.

The last new technology mentioned is copper eating bacteria. These bacteria are introduced to tailing ponds. They eat the copper and then are processed to recover the copper. They improve recovery rates and perhaps bacteria hungry for other minerals could be developed (Mining Technology, 2020). As for bacterial application in Space, it seems questionable whether they could survive in harsh space environments. This leads us to consider the role of humans in space mining. Although the U.S. sent humans for very brief landings on the Moon, Soviet lunar and all other space samples have been obtained robotically. So can we dispense with humans in Space altogether. If not what are the challenges humans would face.

In the sci-fi book *Delta v* (Suarez, 2019), both a robotic mission and a human mission are sent to Ryugu in 2032, which is more than 200 million miles from Earth. The novel demonstrates many of difficulties that such early mining efforts will face: low gravity, isolation, no atmosphere, communication back to Earth taking more than 18 minutes one direction, the need for shielding from radiation, only a short window of opportunity during which Earth return is possible. In the novel, the human mission wins out as the robots are not able to adapt to unexpected problems that disable the robotic mining operations. Thus, the evolution of artificial intelligence will be important in determining whether large scale robotic mining can be done without close by human support.

One of my student, who recently went to work for a chip manufacturer, commented "If you see a human in the plant, you know there is a problem." As problems arising in space mining are likely, at least some humans will likely be needed. National Academies of Sciences (2011) with a lot more horsepower than me also urge a human component in space operations writing "there are widely accepted reasons to continue human lunar exploration that justify the continued investment, commitment, and risk beyond a few missions. The reasons to continue the lunar program include ongoing scientific discoveries, investing in potential commercial development, technology development, educating the next generation of STEM (science, technology, engineering, math) professionals and a scientifically literate public, and inspiring the public about our individual and collective opportunities and future."Whether needed or not, near term plans are to send more humans into Space. The NASA led Artemis mission, with contributions from a number of other collaborators including Canada, Japan, the European Space Agency, and Australia, is expected to land human's on the Moon somewhere around mid-decade or beyond, develop infrastructure for human inhabitants and lay the ground work for eventual human landings on Mars (https://www.asc-csa.gc.ca/eng/astronomy/moon-exploration/artemis-missions.asp, https://www.nasa.gov/feature/nasa-australia-sign-agreement-to-add-rover-to-future-moon-mission). NASA is targeting a crewed mission to Mars near the end of the 2030s (https://www.space.com/nasa-plans-astronauts-mars-mission-30-days). There will be the need to provide life support and protection for their health and well-being.Although one imagines that floating in Space will be quite safe, the health effects are actually rather frightening. Hollingham (2014) outlines numerous such effects. The first hurdle to get through is the take off from Earth or any large body. The acceleration needed to escape Earth's gravity or the deceleration to land safely on Earth puts a great deal of stress on the human body. Stresses of 4 G (4 times the pressure Earth's gravity) and more have been experienced by astronauts (https://www.space.com/42109-soyuz-launch-failure-astronaut-crew-good-health.html). Such stresses from too much gravity for too long a period can cause loss of consciousness, blurred vision, nausea, vomiting, blood pooling in the face or other areas of the body, disorientation or even death.

Once in Space the problems do not go away. Too little gravity also has its drawbacks. Loss of muscle and bone mass began almost immediately. Bone mass may deteriorate at a rate of 1-2% a month. Astronauts have been shown to suffer up to a 20% loss in muscle mass in less than 2 weeks in no gravity. Rigorous exercise and nutritional programs have slowed but not completely mitigated these effects. (https://www.nasa.gov/pdf/64249main_ffs_factsheets_hbp_atrophy.pdf, https://ntrs.nasa.gov/api/citations/20070028552/downloads/20070028552.pdf). Coupling exercise with artificial gravity produced by centrifugal force has been studied and should also be advantageous but the frequency and duration needed does not seem to have been settled upon (https://www.frontiersin.org/articles/10.3389/fncir.2022.784280/full). Such problems accumulate the longer the stay in Space. Longer term, lack of gravity also seems to compromise the immune system (Hollingham, 2014).Too much or too little gravity are not the only challenges we face in Space. Human's evolved to live in roughly 24 hours cycles of day and night. The absence of such a circadian rhythm along with artificial light with too many wavelengths in the blue spectrum has led to sleep deprivation on the ISS. One would expect that special full spectrum artificial lighting could be designed to rectify this problem with more appealing cycles of light and darkness. Such sleep deprivation does not only impair physical function but also may contribute to mental issues. As early as 1982, depression was observed in Space for a Russian cosmonaut aboard the Soviet Salyut 7 space station. The euphoria felt early in a mission may deteriorate as time passes. Crew member clashes, the boredom of repetitive activities and months of institutional food in confined spaces, worry from feeling the constant threats of danger with cold silent Space lurking just outside, and isolation from family and friends may all become more acute as the missions become longer and longer (https://cmsw.mit.edu/angles/2019/headspace-how-space-travel-affects-astronaut-mental-health/). You may recall the psychologist, Deanna Troi, was placed on the starship Enterprise in Star Trek Next Generation for just such eventualities.

Once we have braved the trials of space travel and get where we are going, there are the challenges of space habitation. We can imagine the earliest habitations are likely to be the spacecraft used to get there as in the book *Delta v* mentioned earlier. These fictitious asteroid miners put their craft as living quarters in orbit around Ryugu. They brought the needed equipment and food from Earth, but they were able to generate water and oxygen from the asteroid and make repairs with 3D printing. The craft could also be situated on the surface with local materials used as shielding. NASA (2020) is developing a rover that will combine living quarters, lab facilities, and surface transportation on Mars (https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars

Where permanent habitation is desired, these initial ships, whether situated in orbit or on the surface may bring along enough equipment to develop infrastructure from local materials. This use of local resources is called in situ resource utilization (ISRU). Mueller and Susante (2012) suggest the applications of ISRU that are most likely for exploration and exploitation in Space: prospecting for ore deposits, producing, transporting and storing water, air, and hydrogen for transport fuel and energy, and producing material for constructions and maintenance of equipment and infrastructure.

More permanent habitation in Space also may be in orbit or else on or under the surface of a Space body. Hereafter, I will refer to surface habitats as bases and revolving habitats as stations. We have orbited all the planets in our solar stem but Neptune (Solar System Exploration NASA, 2022) and we have orbited the Moon, Comet 67P/Churyumov-Gerasimenko and the asteroids Eros, Vesta, and Ceres (ESA, 2022). But as of yet we have no permanent crewed stations orbiting any other space body but Earth. Surface habitations abound in the science fiction literature with serious suggestions from the scientific community as well. Ganapathi, Ferrall, and Seshan (1993) survey more than 20 different design types proposed over three decades. Shapes include cylinders, domes, and cubes. They can be underground in lava tubes, in solar craters, and in excavated tunnels with a variety of tunneling methods suggested. One could also imagine mined out areas being used to create underground habitats. If above ground, they need to be made of material thick enough to withstand radiation bombardment or be strong enough to support being buried in regolith or be sheltered in a radiation protective structure. Most have been designed for lunar habitats and vary depending on the number of inhabitants, the length and purpose of stay, and the permanence of the base.

Lewis (1996) suggested when we leave Earth's gravity well, that we will start with a research base on the Moon. Any such habitation will need to provide breathable air, food, water, and livable protective shelter. On Earth, our atmosphere, held down by Earth's gravity, and Earth's magnetic field, created by a molten core, provide breathable air, protect us from solar and cosmic radiation, balance the temperature, and protect us from meteoroids. Liquid water is also plentiful. None of our near-term potential mining prospects – the Moon, NEOs, and Mars–provide such generous environments, which we will then need to provide artificially. Initially all material needs would be brought from Earth, but as we build up capital equipment and adapt to the lunar environment, more and more of the needs could be met by using lunar resources leading to a self-sustaining ecosystem. In addition to basic human habitat needs, we would also need the energy to power all the equipment.

Along with imagined habitation in the world of science fiction, serious scientific studies have imagined lunar habitats that would fit human needs. NASA's earlier proposal for a first lunar outpost was for short stays. A lander would transport the habitation module (a modified version of the international space station module. It was to provide initial habitat for lunar stays of 45 days for 4 inhabitants (Bartz, Cook, and Rusingizandekwe, 2013). It would have power and communication modules, 20 kW solar arrays with water and waste water providing radiation shielding for the array. When the humans returned to Earth the habitat would be stored in remote access mode awaiting further return missions. Successive missions could increase the size and functionality of the habitat including water recycling, oxygen generation from moon materials and exploiting lunar materials for lunar needs. It would provide much needed information for living in Space and the operation would have the possibility of evolving into a permanent moon base. This proposal was never funded. A subsequent study for a two lunar day stay for a crew of two included a Spartan inflatable habitat with a diameter of 2.5 meters and a length of 2 meters (Lindroos, n.d.).

Lewis (1996) also starts with a habitation module brought from Earth, but he buries his module in a trench and covers it with regolith–the rocky material on the Moon's surface–to provide shielding from radiation and meteoroids. The shielding process would be automated and the equipment used could be useful to other projects that would require use of lunar material. If available, water or ice could provide even better shielding from radiation. Initial supplies of water, oxygen and food would come from Earth. The CO2 would be recycled to get back carbon and oxygen. He also considers how a research station might evolve into self-sufficiency to generate its own water, oxygen, and food. When he was writing, water was thought to be in short supply on the moon making it much more difficult to generate oxygen and water. Subsequent missions suggest that water is much more abundant in the form of ice in permanent shaded areas such as the moon's polar craters (Mehta, 2020). The ice could be melted and cleaned if needed to provide water, the water could also be broken into oxygen and hydrogen using electrolysis. The electric current for the trial electrolysis could come from solar energy. Where the process needs heat, solar thermal using a concentrated mirror might be used. With permit and have a tab at take and CO2 could also be used to grow crops that would in turn emit oxygen into the atmosphere. Since a lunar days and nights are roughly 14 hours, the use of solar energy would require stored energy or another energy source for half the time. If panels were located at the lunar poles they could be moves to be in the sunlight all the time, but the similar intensity is less and the temperature variation is higher in these regions. Alternatively, nuclear energy in the form of fission could be used or hydrogen and oxygen separated out of water during this sunlit could be recombined in fuel cells to create electricity when it's dark. The separated oxygen and hydrogen could be liquefied and also used as fuel for the return to Earth or it could eventually become a fueling stop for trips to Mars or elsewhere.

The private sector has seen an increasing role in Space travel, which is likely to continue if we commence with mining in Space. In 2005, U. S. NASA launched its Commercial Orbital Transportation Services (COTS) Program for buying transport services from the private sector. SpaceX in 2006 and Orbital Sciences Corp (part of Northrup Grumman as of 2018) in 2008 were chosen as initial partners in the first phase and given some startup money. Both companies were subsequently awarded commercial contracts. SpaceX first docked at the ISS station in 2012 making subsequent cargo deliveries with it first human cargo delivered in 2020. Orbital first docked at the ISS in 2013 with subsequent cargo deliveries continued by Northrup Grumman in 2018 (Dahl, 2020b). A subsequent contract for cargo deliveries was awarded to Sierra Nevada Corp (Cofield, 2016). All three companies still have contracts for deliveries to ISS 9 (Skibba, 2022), but only SpaceX has contracts for human deliveries (Waldek, 2022).International cooperation as well as public private cooperation have been evolving as well. The ISS with the first segment launched in 1998 is the most visible example to date with more than a dozen countries collaborating (https://www.space.com/16748-international-space-station.html). Upcoming China has announced plans to collaborate with Russia to build an un-crewed space station on the Moon (). The even more challenging Artemis mission already mentioned is targeting crewed missions to the Moon, an orbiting lunar station (Gateway), and a surface lunar base with even more ambitions for Mars. Artemis III is scheduled to launch no sooner than 2025 (Government of Canada, n.d.). NASA (2020a) outlines many of the goals of Artemis III. They include both basic scientific research such as learning about planetary and lunar history and processes as well as space travel related knowledge such as identifying space exploration risks and their mitigation. They include a list of larger goals with an extensive list of sub-investigations in Table 1, p. 125-145. Many of the investigations are directly related to the potential for future mining activities and are questions that need to be asked to help determine the commerciality of mining on the moon. Unless all future mining is totally robotic, the numerous studies relating to the lunar effects on humans are relevant. All the testing on the dynamics, distribution and composition of minerals on the Moon should be helpful as are any tests on in situ construction and processing mineral. (e.g. producing oxygen from lunar regolith, producing oxygen and hydrogen from water ice, sintering regolith in lunar gravity, in situ production of concrete, studying plant growth).

The plan is for initial astronaut stays to be less than a week at a time and the initial surface habitat will be a landing craft built by SpaceX. To be able to lift the weight needed from Earth to the Moon, SpaceX is planning to refuel in LEO (NASA, 2021c) (House, 2021) (iGadgetPro, 2020). Presumable plans for more permanent settlements will be made as more is learned. Thus, these initial forays for human return to Space, have both a surface and an orbiting habitat planned but both are for short term human habitation. Additionally China and Russia recently announced a plan to collaborate on a robotic mission to the Moon in 2025 with a moon base including life support systems completed by 2035 (Liu and Li, 2022).

For permanent longer term communities in Space, the same two basic configurations have been imagined. In O'Neill's version, the first prototype design called Island 1, would be built with material from the Earth and Moon with most subsequent manufactured products being built on the station. These spherical modules about 1.4 kilometers (km) in diameter would each provide living space and highly efficient agriculture areas providing food production for about 10,000 people. Food, water, and atmosphere would be created locally. Manufacturing would be outside the habitat in zero gravity. He envisioned an accumulation of 8 – 16 such modules would form small communities. They would be followed by somewhat larger models he calls Island 2. These 1.8 km spherical modules would provide habitat for around 140,000 people and communities could also grow by adding modules. An Island 2 would be large enough to provide a feasible industrial base but small enough to easily provide efficient transportation within the station. He costs building his space colony at L5 that would include bringing the basic needed materials and equipment to get started from Earth with additional material needed (aluminum, glass, water, soil rock, construction materials) mined and returned from the moon. Converting his costs to 2021 dollars, O'Neill estimates that his smallest colony (called Island 1 above) would cost about $33 billion per year for 8 years to build, while with learning his considerably bigger Island 2 model would cost about $28 billion per year for 8 years

His largest target size, he calls Island 3. For Island 3, each module is a rotating cylindrical station 32 km (20 miles) long and 8 km in diameter (5 miles). Such cylinders have come to be called O'Neill's cylinder's. Two such cylinders could house 8 million people or more, depending on the desired population density. An outer rotating cylinder and a counter-rotating inner cylinder would simulate gravity on Earth would contain the living and agricultural area. Inside these cylinders would be a zero gravity area along the central axis, which would house industrial production and a recreational area. Moveable mirrors facing towards or away from windows could be used to simulate day and night. Atmosphere would need to be artificially created, but pressure would be lower than on Earth at sea level. Oxygen would be obtained from the moon, hydrogen, and nitrogen or an inert replacement for nitrogen would need to come from Earth if not available in space (Kanchwala, 2022)The station would be solar powered with panels positioned to receive sunlight 24X7. Water and building materials would be obtained initially from the moon, which also contains aluminum, iron, titanium, other metals, and silica. Efficient power to transport such materials would be needed. O'Neill suggests one solution would be electromagnetic railguns, he calls mass drivers. These electromagnetic catapults would essentially throw materials to L5 where they would be captured for use in building the space colony as well as provide materials for their manufacturing industries.

Later near Earth asteroids (NEAs) could be mined. Carbonaceous asteroids are thought to be a likely first candidate. They could be mined for water, metals, and carbon compounds. The water could be used to make propellant for growing plants for human consumption and make oxygen for atmosphere on the station. Metal and carbon could be used to make products for 3-D printing. Carbon mixed with oxygen to make CO2 could be used for plant growth in the agricultural area (Metzger, 2013). Some NEAs may contain ammonia and amino acids, which would be sources of nitrogen, that could contribute to the station's atmosphere (Pizzarello, Williams, Lehman, Holland, and Yargera, 2011).

A small share of near earth objects (NEOs) are comets. The Jet Propulsion Lab's Center for Near Earth Objects lists 117 short cycle near Earth comets (NECs) (Jet Propulsion Laboratory, n.d.-c). Such comets, mostly composed of water ice and dust, have orbits around the sun that are 200 or fewer years. If accessible they would provide another source of water for the station. Indeed, it is thought that comets colliding with early Earth may be some of the sources for our planetary abundance of water (Stierwalt, 2019). To move materials from the NEAs and NECs to L5, O'Neill suggests developing barges. Once loaded they would start on their way with piloted space tugs that would get them up to speed and send them on their way. With no atmosphere or gravity to slow the barges down they would continue to coast to their destination without need for onboard pilots. Piloted tugs at the stations would come out and meet the barges to slow them down and guide them into the Space port. Once unloaded the tugs could send them back to the NEA with any supplies needed to support the mining operation.

As stations develop and get richer, there may be a desire for more space per person and station size and design would advance accordingly. Modules and communities could decide on the type of governance and the design for the habitation and recreational areas. Arthur (2018) and Arthur (2020) provide some idea's along these lines.See Holt's critiques and debate on O'Neill's proposals in NSS (n.d.)uggestions of possible trade possibilities are for L5 to produce heavy scientific equipment such as telescopes research spacecraft both manned and unmanned, and laboratories for the study of zero gravity condition. For some of the larger asteroids, there might be the possibility of being hollowed out to provide protection around O'Neill cylinders. Another intriguing suggestion is to convert the asteroid to a spacecraft to move themselves back to the Moon or other mining outpost for processing as suggested in (Dunn et al., 2017). They name their proposal RAMA, Reconstituting Asteroids into Mechanical Automata. They suggest the feasibility of such a process for asteroids as small as 10 m or up to around 100 m.They suggest this methodology for rather small asteroids for the following reasons. Asteroids from 1 to 100 km in diameter have enough gravity so that small rocks and regolith may stick to their surface. However, they are not large enough to have enough interior heat and pressure to have a molten core as is the case for the Earth and Mars. Without such heat, smaller asteroids are likely porous and made out of materials agglomerated together. And they will be relatively easy to break up for ore. Smaller asteroids, less hundred meters in diameter, have too little gravity to hold onto any loosely packed material. They also tend to be rotating fairly rapidly which would require some internal cohesion. With such properties these smaller asteroids would have enough structural integrity to support the conversion into a navigational body.

The solar powered vessel from LEO visiting the asteroid, called the seed craft, would mine and convert enough materials to create propulsion if water is available and a propulsion system and placed in the hollowed out asteroid. Without water or other propulsion volatiles, waste rock is forced out to provide propulsion powered by mechanical means such as an elastic spring or flywheel would provide propulsion. How this is done depends on the type of the targeted asteroid. Once its task is completed it would give the asteroid a push and move it onto to its next target. Their proposed sample mission chosen at the large end of feasibility would commence in 2038, take 30 years to return the asteroid weighing more than 10,000 tonnes to Earth-Moon L5. Smaller asteroids would take less time as would hydrated asteroids that could provide LOX and hydrogen propellants.

Although lunar and mars crewed landings and permanent habitats for them are in the planning horizon, I have not yet encountered any detailed habitat plans (NASA, 2020c). The extensive survey by Ganapathi et al. (1993) seems to cover the needs (oxygen, water, shelter that protects from radiation, solar flares, temperature extremes, and micro-meteorites, basic design types, and the need to use ISRU seen elsewhere. However, continued exploration and technical change suggests that we know more about the materials available, while automation and 3D printing are likely to play a larger role than in early visions. For example, Baiden, Grenier, Blair, and Tietz (2022, Ch.13) suggest that we can build a lunar habitat remotely to be ready for human arrival. The Chinese-Russian plans for an un-crewed lunar base will have to be built remotely as well. Given the terrestrial success of 3D printing (also called additive manufacturing), this seems a quite likely technology that is being researched heavily for both in situ habitat creation in Space as well as making and repairing equipment. (TopTechTopic, 2021). Habitats have been successfully created on Earth using 3D printing and experiments to make smaller pieces have also been successfully conducted on the ISS.

The private sector is also getting in on long-term commercial plans to colonize Space. Jeff Bezos is promoting space colonies based more on the lines of orbiting O'Neill cylinders, while Elon Musk favors a planetary habitation of Mars. Their nearer term activities include less ambitious plans to support lunar bases and LEO orbiting stations as stepping stones. (Hamilton, 2021) While evidence suggests that we are or will be able to mine space, and important question to ask is will be want to. In the next section. I consider economic models that might help us determine the commercial viability of space mining.

7. Economic Feasibility and the Private Sector: Markets for Mined Space Materials

In the beginning, the Space race to leave Earth's gravity well (gravitational field) was conducted by governments. Although improving scientific knowledge was a plus, political motivation and defense were probably even stronger. Being fueled by the cold war, if my rocket is bigger and better than yours, so is my economic system and means of defense. Closer to home and orbiting within Earth's gravity influence, positioning satellites were being developed in the early 1960s, which led to the U.S. Global Positioning System (GPS) completed by 1995 with 24 active satellites. Russia's system GLONASS with some fits and starts became functional again by 2011. Others to follow to full global service are (China's Beidou globally operational around 2020, Europe's privately owned Galileo expected global operations in 2022). Both India and Japan have regional systems (Millner, Maksim, and Huhmann, 2022).

While governments were marching on with exploration and defense, the private market for communication satellites started in 1962 with AT&T's Telstar. It could beam television and telephone signals. Unfortunately, it was killed by radiation in just a few months (NASA Content Administrator, 2012). By 2020, both the government and commercial market had expanded dramatically. There were around 3200 junk satellites and 2666 operational satellites. Of the operational satellites, about 60% were commercial. Commercial communication accounts for around 38% of operational satellites, commercial Earth observation around 17% with navigation and technology development around another 7%. While Eurostat has forecasted almost a 1000 new satellites while be launched per year through 2028 (Wood, 2020). As we move forward, space mining operations might be used for in space refueling and refurbishment of such satellites or eventually even provide materials for in space manufacturing of them.

Most seem to think earth's market for space mined products is fairly limited near term with most of the mined product to be used in Space. Thus, understanding the prospects in the space market will prove essential. Nevertheless, let's start with the current earth market (market 1) with no space mining and build a generic model from there. Start with the simplest models in (Dahl, forthcoming 2023) with one market for one mined good (Q_1). Call the model **M.a**. The market is assumed competitive with sellers and buyers responding to earth's price (P_1) as represented by the following supply and demand equations and figure 4.

$Qs_1=S_1(P_1)$ (M.a)

$Qd_1=D_1(P_1)$

Equilibrium $Qs_1(P_1)=Qd_1(P_1)$

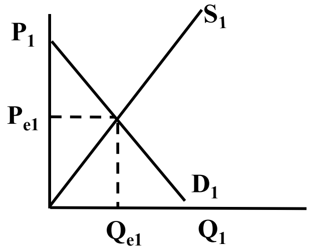
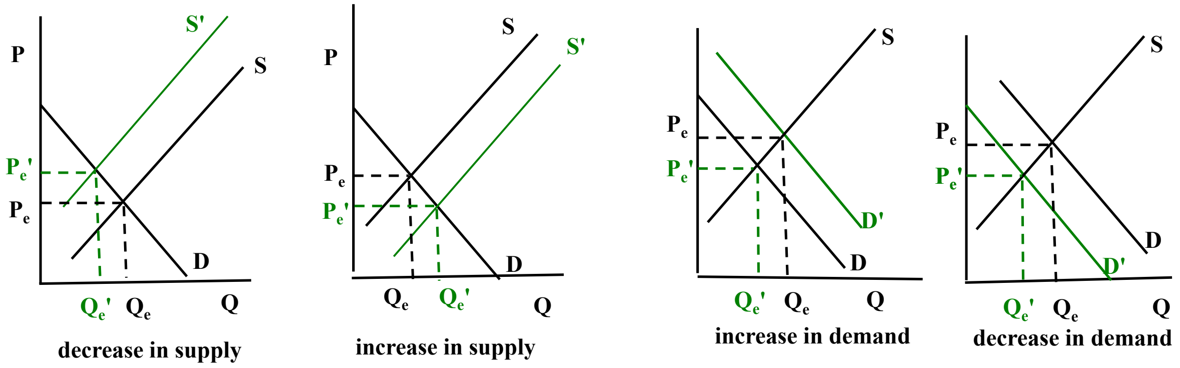


Figure 4 Equilibrium in model M.a

M.a represents a competitive market with neither side of the market having control over price. Demand represents the marginal benefits of the mined material and supply represents the marginal costs of the mined. If the market structure changed, giving the buyer market power, we would expect the buyer to push the price below the competitive price. If instead, the market structure changed and the seller had market power, we would expect the seller to push the price above the competitive price. If both sides of the market had market power, the end price would result from negotiations. The outcome would depend on the side with the better bargaining position. We would have a lower ability to anticipate the market price, but might be able to anticipate the range of prices where neither side would definitely drop out of the market. Equilibrium in the above market is at price P_{e1} and quantity mined and sold of Q_{e1}.

Over time changing economic activity, technology, prices of other goods, and other things will shift demand and supply and trace out new prices with some examples shown in Figure 5.



decrease in supply

increase in supply

increase in demand

decrease in demand

Figure 5: The effect of shifting demand and supply on price in model M.a

The price increase is likely to be up for a decrease in supply or increase in demand or down for an increase in supply or a decrease in demand. In reality, both curves are typically shifting over time. Since mining is highly capital intensive with mines taking many years to develop and many subsequent years to produce, prospective mine owners would not only consider price right now, but would want to know prices over the life of the project.

Prospective investors in new mining operations in market 1 will want to know the likely future trajectory of prices as well as the timing and amount of needed investment. and will likely consider the expected net present value of their investment in a new mine given as:

$$\mathrm{NPV} = \sum_{i=b}^{b+n} \frac{P_{1,i}\times Q_{1,i}}{(1+r)^i} - \sum_{i=0}^{b+n}\left(\frac{C_{1,i}}{(1+r)^i} + \frac{c_{1,i}\times Q_{1,i\cdot}}{(1+r)^i}\right) \quad (3)$$

Where b is first year the mine sells the final product to Earth's markets, n is the productive life of the mine, $Q_{1,i}$ is the delivery of mined material to market 1 in year i, $C_{1,i}$ is the fixed capital cost spent in year i in market 1, it would include the huge up front capital cost, fixed cost maintenance and investments along the way and reclamation costs at the end of mineral production, $c_{1,i}$ is the annual unit operating cost in year i, and r is the required rate of return or discount rate. Where $C_{1,i}$ is zero if no fixed costs are incurred in year i, and $Q_{1,i}$ is zero if no output is produced in year.

Alternatively, we could levelize or distribute the capital or fixed cost over each unit of production by solving the following equation for Lc (Dahl, 2015, p 301).

$$\sum_{i=0}^{b+n}\left(\frac{C_{1,i}}{(1+r)^i}\right) - \sum_{i=0}^{b+n}\frac{Lc \times Q_{1,i}}{(1+r)^i} = 0$$

Using the levelized cost (Lc) the NPV equation becomes:

$$\mathrm{NPV} = \sum_{i=b}^{b+20} \frac{(P_{1,i} - Lc - c_{1,i})\times Q_{1,i}}{(1+r)^i} \quad (4)$$

Investors would want the above NPV to be positive to undertake new mining endeavors.

One of the early justification to mine Space was to compensate for depletion on Earth or to bring back scarce and expensive metals. Kargel (1994) argues that precious metals, if mined and separated in situ (on the space object), might be profitably brought back to earth markets. He bases his analysis on metallic asteroids greater than 1 km in diameter and reckons there are six such NEA's based on inventories of NEAs at the time. He recognizes that bringing large amounts of precious metals into Earth markets will lower the price, and he spreads his asteroid based metal sales over 20 years. He acknowledges, however, that we don't know the technology to separate PGM's on asteroids, nor do we know what the missions will cost. But let's suppose we figure it out.

To model this second case, (model M.b), let's add an upward sloping supply curve of material from Space, which will be market 2. Ignor transport cost within Earth's market but assume the cost of transporting a tonne of ore from Space back to Earth is τ/tonne. With a competitive market, production profitable on both Earth and in Space, and no bottlenecks for Earth return, arbitrage should cause:

$$P_1=P_2+\tau \qquad (5)$$

P_1 is the on Earth and P_2 is the mine mouth price or returns to the mine in Space. If P_1 is greater in equation (5), we can get the material in Space for P_2 and transport it back at τ for less than buying it on Earth. With upward sloping supplies, this shift towards buying more material in Space and less on Earth should lower the price on Earth and raise the price until equality has been restored. If P_1 is less in equation (3), the opposite would happen raising Earth price on and lowering the price received in Space. The model M.b. We can write model **M.b** as:

$$Qs_1=S_1(P_1) \qquad \text{(M.b)}$$
$$Qd_1=D_1(P_1)$$
$$Qs_2=S_2(P_1)$$
$$\text{Equilibrium } Qs_1(P_1)+Qs_2(P_1)=Qd_2(P_1)$$

Since P_2 always equals $P_1-\tau$. We can write the supply equation as a function of P_1,so we can keep the model in two dimensions and represent it graphically. Equilibrium is when total supply equal to quantities from Space and quantities from Earth satisfy the quantity demanded on Earth. We represent this new situation in Figure 5. The original Earth model is represented on the left. Space supply is represented in the center. Notice if the price is below a in the center market, space will not product anything. At each Earth price, add what Earth would supply and what Space would supply at that price. The new combined supply S1+S2 is shown in the earth's market on the right. Where the new supply crosses demand determines the new equilibrium at $P_{e1'}$.

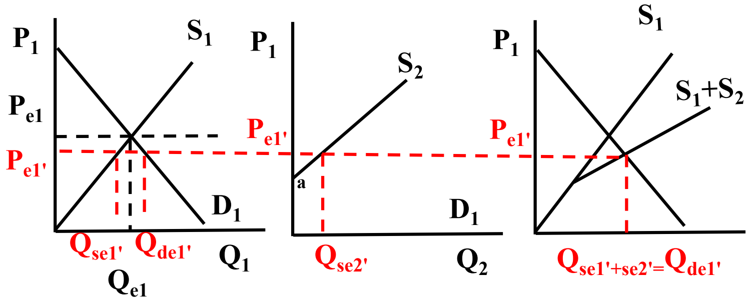


Figure 5 Equilibrium in Model M.b Earth Market Plus Space Suppliers

Notes: Values without primes in black font show equilibrium without a space market, and values with primes red font show the new values once we add a space market.

On the right you can see the new total equilibrium quantity demanded on Earth ($Q_{de1'}$), the new equilibrium price on Earth ($P_{el'}$), and total equilibrium quantity supplied on Earth (Qse1'+Qse2'). Since the price is above a, there is supply from Space. Seeing the separate quantities supplied from each market can be determined but may be easier to discern as labelled in the markets on the left and center. We can't see the mine mouth price in space but could determine it from $P_2-\tau$.

Although researchers have envisioned bringing Space materials back to Earth, in reality we have not done so yet commercially. We have, however, used Earth materials in Space. Governments have needed Earth materials in Space for exploration missions and satellites, while the commercial space sector on Earth has been busily launching satellites that orbit the Earth for many decades. A registry of these satellites including their launch date, owner, and orbital status is maintained by the United Nations at https://www.unoosa.org/oosa/osoindex/search-ng.jspx?lf_id with data going back to 1975.

So now instead of adding a space supply, let's add a space demand to our original market model (M.a). Instead of raw materials, our markets are further along the supply chain and are for goods processed from mined materials. For a likely representation of the Space market turn to the six digit North American Industry Classification System (NAICS). Two codes would include the current space market Code 927110 ". . . government establishments primarily engaged in the administration and operations of space flights, space research, and space exploration. Included in this industry are government establishments operating space flight centers" and Code 517410 ". . . establishments primarily engaged in providing telecommunications services to other establishments in the telecommunications and broadcasting industries by forwarding and receiving communication signals via a system of satellites or reselling satellite telecommunications."

The unit cost of transporting materials from Earth to Space is τ. Again assume the effect cost of the goods in the two markets $P_2=P_1+\tau$. Then we can write space demand as a function of P_1. New equilibrium will be where Earth quantity supplied equals Earth plus space quantity demanded. Then we can write this model (**M.c**) as:

$Qs_1=S_1(P_1)$ (M.c)

$Qd_1=D_1(P_1)$

$Qd_2=S_2(P_1)$

Equilibrium $Qs_1(P_1)=Qd_1(P_1)+Qd_2(P_1)$

You can compute P_2 from $P_1+\tau$, once the model is solved. You could also generalize this and make τ a function of Qd_2 as long as you can solve for Qd_2 as a function of P_1. To visualize the solution, see space demand graphed in terms of P_1 in the middle below. The space market has been exaggerated to be able to see an effect graphically. If the price is above b, there will be no demand in space. On the right, add together Earth quantity demanded and space quantity demanded and find the Earth price where the equilibrium holds, again labelled $P_{e1'}$. As the price is below b, there is material consumption in Space.

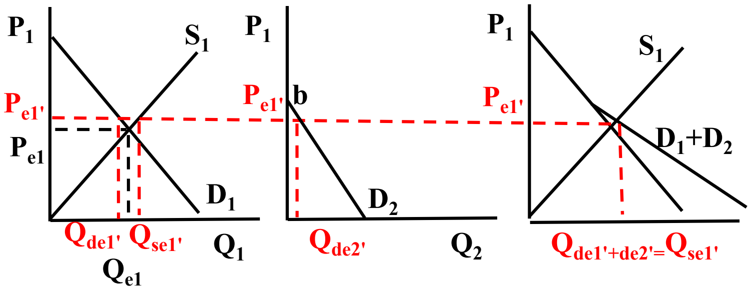


Figure 6: Model M.c Space Demands Earth Materials But Does Not Produce Any Materials

Notes: Values without primes in black font show equilibrium without a space market, and values with primes in red font show the new values once we add a space market.

You can discern material consumption in Space plus on Earth as well as total earth production on the left. You can also see earth and space consumption separately in the markets on the left and center, respectively.

Implementing the above model, even though a trivial mathematical exercise to solve, would present some interesting challenges in developing inputs. A number of estimates for demand and supply for separate minerals on Earth have been conducted (See (Dahl, 2020a)) and using the supply and demand elasticities from them gives us a place to start as in (Dahl et al., 2020). However, less is known about the current space market. We could try to estimate space demand from historical data. If we were working with mineral markets, the demand for space services would have to be translated into mineral demand and the Earth equations would also have to be aggregated into the minerals used in space industries. I leave it to the reader to work it out on the back of envelopes. If you need used envelopes for the computations, let me know, I have a considerable stockpile recycled from junk mail.

Early on, many have suggested that asteroid mining for space use will begin with water, regolith and other materials for building infrastructure. Although abundant on Earth, such mundane products are expensive to move into space. The cost of moving a kg to LEO has fallen from $85,000/kg in 1981 to around $950 in 2020, but it still means that a tonne of rolled steel priced at around $540 per tonne on Earth in 2019, would cost more than $950,000 to LEO and water would cost almost as much. Getting them to the Moon or Mars would cost considerably more.

I consider the prospect of both demand and supply in Space in model M.d by adding space supply to model M.c. I assume no transport costs within the two markets but transport costs of τ per unit across the two markets. If there is trade across the two competitive markets, arbitrage makes $P_2=P_1+\tau$, so again we can write and graph all our functions in terms of P_1.

$$\begin{aligned} &Qs_1=S_1(P_1) && \text{(M.d)} \\ &Qs_2=S_2(P_1) \\ &Qd_1=D_1(P_1) \\ &Qd_2=D_2(P_1) \\ &\text{Equilibrium } S_1(P_1)+S_2(P_1)=D_1(P_1)+D_2(P_1) \end{aligned}$$

Model M.d is shown in figure 7. In the graph on the left is model M.c. Since the graph is getting quite busy, I dispense with showing the solution to model M.c. In the center of the figure is the supply of material from Space. On the right is the new space supply quantity added to Earth supply quantity. Equilibrium price is seen on the aggregate market on the right where Earth plus Space supply equals Earth plus Space demand ($Q_{se1'}+Q_{se2'}= Q_{de1'}+Q_{de2'}$) at a price of $P_{1e'}$. From the left side of the figure or the right side, we can see at this price, earth's quantity supplied is $Q_{es1'}$ and is less than Earth quantity demanded of $Q_{ed1'}$. Thus, Earth is a net importer of the material. Space quantity supplied is most easily read off the center of the figure as $Q_{es2'}$. Since there is no separate space demand equation, we would have to surmise $Q_{ed2'}$ from $Q_{ed1'}+Q_{ed2'}-Q_{ed1'}$.

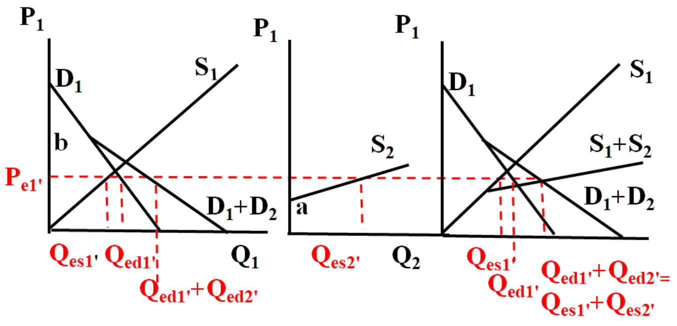


Figure 7: Model M.d Both Earth and Space Demand and Supply the Material

Dahl (forthcoming 2023) considers the above market from the point of view of prospective space miners. They have the possibility of sending the materials to the earth market or the space market. We can see what demand the space miners face by rearranging the equilibrium equation in M.d below in equation (6).

Equilibrium $S_2(P_1) = D_1(P_1)+D_2(P_1) - S_1(P_1)$(6)

Total demand for space miners is then total demand in Space plus demand on Earth minus what Earth supplies. If space miners supply more than this difference, the market will be oversupplied driving price down until the market is in balance. If they supply less it will drive the price up until equation (6) is satisfied. We can write the model from the miner's point of view (M.e) as

$Qs_1=S_1(P_1)$ (M.e)
$Qs_2=S_2(P_1)$
$Qd_1=D_1(P_1)$
$Qd_2=D_2(P_1)$
Equilibrium $S_2(P_1) = D_1(P_1)+D_2(P_1) - S_1(P_1)$

See the situation in the market below. In the left graph is the market from M.c without space supply. In the center is space supply. From the left market, we can compute residual demand for space from $D_1(P_1)+D_2(P_1)- S_1(P_1)$. Again notice if price were above c, Earth would supply a larger quantity than is demanded and price would fall. Add space supply to the diagram on the left and find the space quantity supplied and find equilibrium Earth price ($P_{e1'}$). At that earth price you can see earth quantity supplied ($Q_{es1'}$), earth quantity demanded ($Q_{ed1'}$), and earth plus space quantity demanded ($Q_{ed1'}+Q_{ed2'}$) in the graph on the right. Notice that Earth quantity demanded is greater than Earth quantity supplied, so the Earth is a net importer from Space of $Q_{de1'}-Q_{se1'}$. Since there are only two markets, these earth imports must equal space exports ($Q_{es2'}-Q_{ed2'}$).

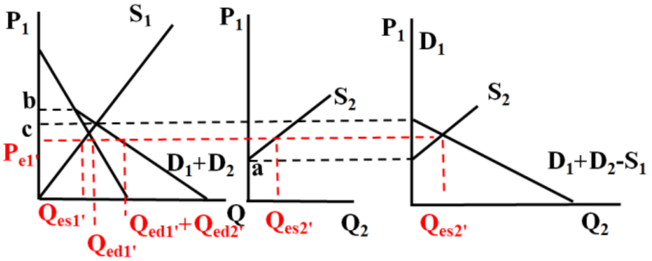


Figure 8: Model M.e from Space Miners View Point with Space Demanding and Suppling
Note: In this case, Earth is a net importer ($Q_{ed1'}-Q_{es1'}$)

You could play around with the above diagrams shifting demand and supply in each market and come up with number of different cases. For example in Dahl (forthcoming 2023), the Earth is a net exporter. In this case, assume that technical change improves mine productivity on Earth and Earth supply increases compared to M.e. Can you see this case (M.e') in Figure 9.

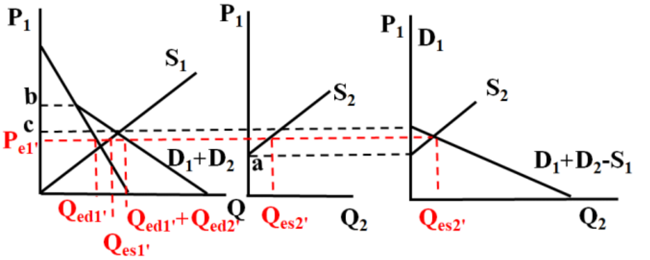


Figure 9: Model M.e' from Space Miners View Point with Space Demanding and Suppling
Note: In this case, Earth is a net exporter of $Q_{es1'}-Q_{ed1'}$)

We can come up cases where one of either Earth of Space supply both markets. Take case M.e" where space costs are so high that Earth supplies both Earth and Space. The price at which Space can enter the market (a) is above the price where Earth can supply both markets. Despite astronomical amounts of material in Space, this is the current situation in which high processing costs in Space, high transport cost back to Earth or a combination of both, which makes Space mining not yet noncompetitive.

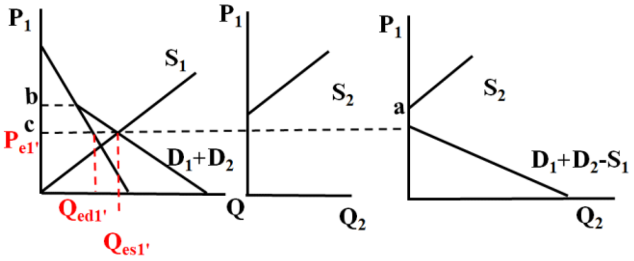


Figure 10: Model M.e" from Space Miners View Point with Space Demanding and Suppling
Note: In this case, Earth supplies the whole market $Qes1'=Q_{ed1'}-Q_{ed2'}$.

Alternatively, if in the future we have severely depleted Earth mineral supplies and we have developed the technology to more cheaply produce and deliver vast mineral supplies from the main asteroid belt, earth suppliers could become non-competitive. We can illustrate this situation in the more complicated situation in Figure 11 on the left. It shows demands in both markets and earth supply. From these functions we can develop the space demand equation as on the right from $D_1(P_1)+D_2(P_1)-S_1(P_1)$. At c, Earth has the whole market and is satisfying the quantity demand on Earth. The price is too high so Space demands nothing. At a price above c, Earth would supply a larger quantity than Earth demanded. The excess quantity supplied would push the price down to c. Between c and d, Earth is not supplying the whole market but the price is still too high for space demanders, so the demand left for Space is $D_1(P_1) - S_1(P_1)$. Below d, Earth does not produce, so Space has the whole market $D_1(P_1)+D_2(P_1)$.

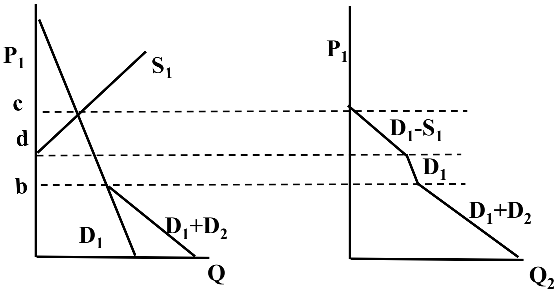


Figure 11: Model M.e"' More Complicated Space Miner Demand.

Where we end up depends on completing the model with a space supply function. Figure 12, gives 4 supply cases in panels (I) to (IV) for the space demand given on the left in Figure 11. In panel (I), space supply is largest. It has driven price low enough so that earth supply is not competitive and Space is supplying the whole market. We can read the equilibrium price on Earth (P_{e1}). To learn the equilibrium price in space, we would need to know and subtract the transport cost from Space to Earth. We know Space is supplying both the earth and space market, so we know the equilibrium quantity supplied but not the breakdown of that quantity demanded between the earth and space market. To find that out, we would need to go back to the total demand curve on the left in Figure 11. At P_{e1}, we could read off Q_{ed1}, from D_1, and compute Q_{ed2} from $Q_{ed2}= Q_{es2}-Q_{ed1}$.

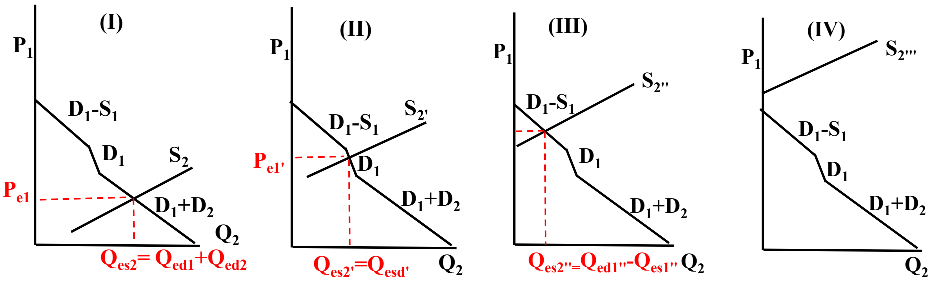


Figure 12: Model M.e''' with Space Demand from Figure 11Demand Curve

In panel (II), space supply is smaller and crosses at a price that is too high for space demanders but too low for earth suppliers. For this case, equilibrium price on Earth is $P_{el'}$. Only Earth is consuming the mined material ($Q_{ed1'}$), and only Space is supplying this amount of material ($Q_{es2'}$). To know the space price, again we would need to know transport costs.

In panel (III), space supply is smaller yet and crosses at a price that is too high for space demanders but now high enough for earth suppliers. For this case, equilibrium price on Earth is $P_{el''}$. Space is supplying $Q_{es2'}$ to Earth. To find out total equilibrium earth quantities demanded and supplied, we would need to go back to the total earth demand and supply curves on the left in Figure 11 and read the quantities for $P_{e1''}$.

Panel (IV) has cost in Space so high, space supply does not cross space demand. We are back to our original situation in figure 4, with only material being consumed and produced on Earth. Now the space and earth markets are no longer connected and the arbitrage equation does not hold ($P_{e2}\neq P_{e1}+\tau$) since there is no space price. So even though the model M.e is still quite simple and unrealistic, with the possibility of corner solutions (where some players are not in the market and produce or consume none of the material), it has gotten considerably more complicated.

For all these cases, if the prospective space miner wanted to compute NPV in equation (4) over the life of the project, she would need to forecast the timing and amount of space price, quantity, and operating costs including transport and processing for each year, levelize the cost of capital over this forecasted production profile, and pick the appropriate discount rate.

The above models give us intuition allowing us to visualize market equilibriums, yet they are quite simple and unrealistic. Even the cases in M.e, which are more complicated, are still quite simple. As we move to increase realism further, it is time to move to mathematical modelling with computer solutions. (Dahl, forthcoming 2023) indicates some of the assumptions that will need to be relaxed to do so. Transport costs will need to be included both within and across markets. Transport costs may not be symmetric. Transport cost from a large body with an atmosphere are likely to be higher than transport costs to the large body. An atmosphere provides aerodrag slowing the ship down when leaving the gravity well of a large body but helps by slowing down an incoming craft to prevent a crash landing. Arbitrage allowed us to represent all graphs in terms of Earth's price. However, if markets are disconnected as in model M.e''' case (IV), the arbitrage condition will need to be relaxed.

To add in such complications, let's work out a mathematical model for this slightly more complicated model in preparation for building a more general model in with multiple types of space materials and multiple space mining operations in (Dahl, forthcoming 2023). First modify demand and supply in model M.e to allow for internal transport costs and the possibility of no arbitrage as follows.

$$Qs_1=S_1(P_{s1}) \qquad \text{(M.f)}$$

$$Qs_2=S_2(P_{s2})$$

$$Qd_1=D_1(P_{d1})$$

$Qd_2=D_2(P_{d2})$

In such a case, we can have four different demand and supply prices (what demanders pay in each market and what suppliers receive). In the above models, we visually could see that the whole market and individual markets were satisfied. Mathematically equilibrium requires that overall supply must equal overall demand as above.

Overall equilibrium $S_1(P_{s1}) + S_2(P_{s2})=D_1(P_{d1}) + D_2(P_{d2})$.

We must also assure that each individual market is in equilibrium, which we do as follows. Let x_{ij} be the flow of material from supply i to demand j. Then what supply 1 produces must equal what supply 1 sends to demands in 1 and 2.

$S_1(P_{s1})=x_{11}+x_{12}$

Similarly

$S_2(P_{s2})=x_{21}+x_{22}$

What demand 1 buys must equal what supply 1 and supply 2 sells to them.

$D_1(P_{d1}) = x_{11}+x_{21}$

Similarly

$D_2(P_{d2})= x_{12}+x_{22}$

These four equations can be represented as

$S_i(P_{si})=\sum_{j=1}^{2} x_{ij}$ for i = 1, 2

$D_j(P_{di})=\sum_{i=1}^{2} x_{ij}$ for j = 1, 2

Often modelers make the assumption that supply must cover or more than cover demand and then the above two equations are written as inequalities:

$S_i(P_{si})\geq\sum_{j=1}^{2} x_{ij}$ for i = 1, 2

$D_j(P_{di})\leqslant\sum_{i=1}^{2} x_{ij}$ for j = 1, 2

Now there are transport costs within and across markets. Let the cost of transport from supplier i to demander j be τ_{ij}. Next if markets are connected, arbitrage conditions would also need to hold. Thus,

If Earth sells to Earth's market: $Ps_1+\tau_{11}=Pd_1$

If Space sells to space's market: $Ps_2+\tau_{22}=Pd_2$

If Earth sells to space's market; $Ps_1+\tau_{12}=Pd_2$

If Space sells to earth's market: $Ps_2+\tau_{21}=Pd_1$

If there is no trade flow from supply i to demand j ($x_{ij}=0$), the arbitrage condition need not hold. Modelers typically represent these arbitrage conditions as

$(P_{si}+\tau_{ij}-P_{dk})x_{ij}=0$ for i=1,2 and j=1,2.

In the above model, we visually handled when one or the other market player dropped out of the market. In a mathematical model, we would need to require that each supply and demand quantity not allowed to be negative. Nor could any trade flows or prices be negative:

Q_{d1}, Q_{s1}, Q_{d2}, $Q_{s2} \geq 0$

$x_{ij} \geq 0$ for i=1, 2 and j=1, 2

$P_{dj.}$, $P_{si} \geq 0$ for i=1, 2 and j=1, 2

If realistic functions can be developed for the supply and demand equations, and transport cost, the above model could be solved for all trade flows x_{ij}. If the model solves, these trade flows and the equations in the model would determine prices and quantities demanded and supplied in all markets.

With our initial forays into Space mining, there may be supply from only one space source as in the above models. Common suggestions for what that source may be include the Moon, Mars, and near earth asteroids or comets. As time passes we might expect trade networks to evolve as in Niven (1975). Dahl (forthcoming 2023) presents the following model (M.g) which generalizes model M.f to n_j demand nodes, and n_i supply nodes. The following conditions hold for all i = 1, . . .n_i and for all j = 1, . . .n_j

Her supply and demand equations at node i and j, respectively, are:

$$Qs_i=S_i(Ps_i) \qquad \text{(M.g)}$$
$$Qd_j=D_j(Pd_j).$$

Transport cost and material flow from supply node i to demand node j, respectively, are:

τ_{ij} and x_{ij}.

Arbitrage requires:

$$(P_{dj}-P_{si}-\tau_{ij})x_{ij}=0$$

Equilibrium conditions for supply and demand can be summarized, respectively as:

$$S_i(P_{si})=\sum_{j=1}^{n_j} x_{ij}$$
$$D_j(P_{dj})=\sum_{i=1}^{n_i} x_{ij}$$

Nonnegativity constraints are:

$$x_{ij} \geq 0,\ P_{si} \geq 0,\ P_{dj} \geq 0,\ Q_{dj} \geq 0,\ Q_{si} \geq 0.$$

With constraints on the number of transport vessels available, there may be upper bounds on the transport flows.

If the model is solvable, it would give trade flows (x_{ij}), which in turn would indicate prices, quantities supplied and profits at each mine and end-use prices and quantities demanded in each market. However, over the life of the mine, mine managers would need to forecast shifts in the functions across time and resolve.

Dahl (forthcoming 2023) notes that if all of the equations in the above model can be parameterized, it can be solve as a mixed complementarity problem (MCP) in a variety of modeling languages including two of the more popular AMPL and GAMS. Kwon (2019) notes that the more general MCP subsumes a variety of more restrictive models. If all the equations are linear, and there are as many equations as unknowns with only non-negativity constraints, the problem can be solved as a linear complementarity problem (LCP). If we add upper bound constraints to the LCP, it is a mixed linear complementarity problem. If the problem is like the LCP except there are non-linear equations, it is a nonlinear complementarity problem (NLP). If we add upper bound constraints to the NLP, we have a mixed complementarity problem (MCP). Such problems are solved with a variety of solvers. Billups, Dirkse, and Ferris (1997) compares a variety of solvers. For the problems they tested, they found that the solvers Path, Smooth and Proxi performed the best. (Murphy, Pierru, and Smeers, 2016) provide a tutorial on building MCP models for policy analysis.

Moving on we could complicate the above model in all sorts of ways to make it more realistic. Up to now, we have assumed there are no economies of scale in transportation. To add economies or diseconomies of scale in model, we could make τ_{ij} a function x_{ij}. Then τ_{ij} would be endogenous. If there was some transport constraint such as a maximum number of tonne miles each supplier's fleet of ships or that all the ships could carry at time t, we could keep track of the tonne kilometers (k_{ij}) for each x_{ij} and add the proper constraint. Setting up such a model between markets where constraints are binding is a little tricky as arbitrage conditions are not likely to hold in markets where constraints are binding. (Coleman, 2009) considers transport constraints in an even trickier environment. His model also includes inventories and stochastic production.

In the above markets, there is one material mined in Space. However, as the space market evolves, it is likely that more than one material will be mined in Space and we will want to mine additional materials. Suppose as we add materials mined, they are not economically related. Thus, each material is neither a complement nor substitute in demand or supply for the others. In such a world, if we had k separate materials, we would need supplies, demands and transport cost for each material and time could run the model for each material k and t separately.

On Earth, we do not find all materials are economically independent. Aluminum and copper are both electricity conductors and both can be demanded for electricity wiring. Although copper is the better conductor, cheaper aluminum may be used and changes in the price of one of the metals may influence the quantity demanded of the other. If two metals are used together in alloys, such as steel and chromium, they are more likely complements in demand. As some metals are often found together in the Earth, they may be complements in supply or one metal may be a byproduct of producing another, as is the case for the platinum group metals or REEs. Alternately, for metals not found together, if one metal becomes more valuable, miners may switch away from producing less valuable materials towards more profitable ones. The cross price effects or how the change in the price of one material influences the quantity demanded or supplied of another tells us whether the relationship is one of complementarity or substitutability. For example, suppose we have two products k_1 and k_2. If the demand price for k_1 increases ($\Delta Pd_{k1} > 0$) and the quantity demanded for k_2 increases ($\Delta Qd_{k2} > 0$), then k_1 and k_2 are likely substitutes in demand. We typically write this condition for two good as $\Delta Qd_{k2}/\Delta Pd_{k1} > 0$ implies the two goods are substitutes in demand. Then $\Delta Qd_{k2}/\Delta Pd_{k1} < 0$ implies the two goods are complements in demand and the signs of these expressions are switched for supply. Thus $\Delta Qs_{k2}/\Delta Ps_{k1} > 0$ implies the two goods are complements in supply and $\Delta Qs_{k2}/\Delta Ps_{k1} < 0$ implies the two goods are substitutes.

To incorporate such relationships into our model, we will need to include the prices of substitutes and complements in the demand and supply equations. With these relationships across the markets, we cannot run each market model separately but will need to run them altogether as one big system. In the simplest case, adding one substitute and one complement at each supply node i and each demand node j for product k ($Pd_{jk,c1}$, $Pd_{jk,s1}$, $Ps_{ik,c1}$, $Ps_{k,s1}$), we can generalize M.g to M.i as follows:

The supply equation at node i for product k would be: (M.i)

$$Qs_{ik}=S_{ik}(Ps_{ik},Ps_{ik,c1},Ps_{ik,s1}) \text{ for } i = 1, \ldots n_j,\ k = 1, \ldots n_k$$

The demand equation at node j for product k would be:

$$Qd_{jk}=D_{jk}(Pd_{jk},Pd_{jk,c1},Pd_{k,s1}) \text{ for } j = 1, \ldots n_j,\ k = 1, \ldots n_k$$

Arbitrage conditions would still need to hold for all i, j, k:

$$(P_{jk}-P_{ik}-\tau_{ijk})x_{ijk}=0$$

Next, we need the equilibrium conditions. Supply from each node has to equal its demand for each product. Thus, supply from node i product k must equal total demand for it:

$$S_{ik}(Ps_{ik}, Ps_{ik,c1}, Ps_{ik,s1}) = \sum_{j=1}^{n_j} x_{ijk} \text{ for all i and k} \quad (13)$$

And demand from node j for good k must equal total supply to it:

$$D_{jk}(Pd_{jk}, Pd_{jk,c1}, Pd_{jk,s1}) = \sum_{i=1}^{n_i} x_{ijk} \text{ for all j and k}$$

Also, we cannot have negative prices or negative product flows, yielding three more sets of constraints:

$x_{ijk} \geq 0$ for all i, j, k

$Ps_{ik} \geq 0$ for all i, k

$Pd_j \geq 0$ for all j, k

In the above market, each of the k markets has the same number of supply and demand nodes (n_i,n_j). We could alter that if we wanted to bury ourselves in yet more subscripts. The above models all assume competitive markets and their specifications and solutions methods are well established.

There are many ways we could further complicate the models. Certain forms of non-competitive behavior could be assumed as in Graham, Thorpe, and Hogan (1999). They run a spatial global trade model for the coking coal market under perfect competition and five other non-competitive market. In their model there are 6 buyers: Japan, Chinese Taipai, S. Korea, India, the European Union (EU), and Brazil with 4 suppliers Australia, U.S., Canada, Rest of World. The five non-competitive market structures are: 1. Australia as a dominant player with the rest of the suppliers a competitive fringe; 2. the U.S. and Australia act as Nash-Cournot duopolies with the rest of the suppliers as competitive fringe, 3. Japan is a monoposony with the rest of the demanders acting as a competitive fringe, 4. Japan and the EU act as duopsonies with the rest of the demanders acting as a competitive fringe, and 5. all demander act as Nash Cournot oligopsonies. They compare simulated trade flows with actual trade flows in 1996 and found that the fifth non-competitive market (all demanders acting as Nash-Cournot oligopsonies) provided the best fit. These market models would require the same input information as in the competitive models.

Again the model specification and solution methods are well established, but parameterizing the equations even in these well established earthly markets with known processing and transport is still difficult and fraught with uncertainties. Parameterizing new space markets with very limited information on processing and transportation technological, unknown evolution of space industries and market structure present even more challenges. Nevertheless, some clever and enterprising souls have given it a try.

Many existing space mining studies parallel the sci-fi mission in Suarez (2019) favoring the commercial mining of asteroids. Both a robotic and a crewed mission are included and will send the asteroid ore back to cis-lunar orbit (a space between the Earth and the Moon) for processing. Processing in orbit would avoid the extra cost of landing the ore on either the Earth or the Moon; the processed material such as precious metals might be sent to the Earth but more of the material would likely be used in cis-lunar space to fund Space activities for Earth or further afield. Sonter (1996) surveys earlier scientific studies arguing for mining of asteroids beginning with Cole and Cox (1964), while (Hein, Matheson, and Fries, 2020) bring the survey more up-to-date.

Although decades of argument have seemed to favor asteroids for commercial mining, the current expectation is that we may begin our first space mining on the Moon with Artemis and other planned government led missions. Spudis (2014) has argued in favor of the Moon first for a number of reasons. Water, a likely early target, will be hard to extract on asteroids as it is bound up with phyllosilicates. Since yield will be low, its extraction will require significant throughput needing significant energy, equipment and intelligent oversite. He argues we do not yet have the technology to set up such large scale operations. Nor do we yet have the technology for oversite with communication time delays to NEAs or the alternative of totally autonomous mining. Thus, he argued to develop the technology on the Moon where water is available as ice and we only have a 3 second time delay.

Spudis notes the second element often cited as a potential asteroid mining target to be returned to Earth is platinum. Here again he poses some difficulties. Proponents of asteroid mining suggest the Mond process to separate out platinum for Earth return. Platinum is often found with other platinum group metals and with even higher concentrations of iron and nickel in asteroids. Spudis argues that in the Mond process, the metallic ore is granulated and heated to about 100 °C in around 10 atmospheres of pressure in the presence of carbon monoxide. The carbon monoxide joins with nickel and iron carbonyl in the form of a vapor. These carbonyls can be condensed into metal films with platinum left in the residue to be sent back to Earth. The residue may be 50,000 ppm, which is much higher than the original material more likely on the order of 100 ppm (MIT, 2016). Although this process is fairly simple on Earth, Spudis has a number of reservations for doing so on asteroids. These bear some similarities to those for water production: how do we collect and store the carbonyls? How do we get the complicated equipment and large amounts of energy needed for their operation? Can we do this without human oversite? He provides additional information on operational, scientific, and resource utilization aspects for asteroids in Spudis (2011a), Spudis (2011b), and Spudis (2011c). Although the moon is always there in roughly the same relative position, the asteroids orbit the sun, not the Earth and constantly change their relative position. Furthermore, the NEOs thought to be the most valuable for space mining are carbonaceous chondrite and metallic, which are estimated to be only 3% and 7% of all NEOs. Thus orbital mechanics may give us limited launch windows to the best asteroid targets (Spudis, 2011c).

Lewis (2015), a well-known expert on mining asteroids and still a strong advocate of asteroid mining, suggests that we will begin by mining water for fuel in space, followed by materials for space habitat and operations and platinum will be a byproduct sent back to Earth (Tedeschi, 2015). Thus, he implies an ability to separate out the platinum.

Andrews et al. (2015) evolved out of a Senior Space Design Class at the University of Washington to do an economic analysis of a mission to mine NEAs. They have developed an impressive amount of detail for their 25 year mission on asteroid prospectors, launch systems related to space transportation, mining equipment, and a material processing hub. They assumed available or expected technology at the time and target their mining and processing equipment to handle either carbonaceous chondrite or metallic asteroids using a nuclear reactor to fuel their mission. Water and PGMs are separated out from the other materials. They anticipate two or three space operation systems higher than low Earth orbit that can serve as low gravity research centers, provide tourist facilities, take delivery of critical metals (with an implied price of around 24.5 million dollars a tonne in 2021 USD) for transfer to Earth and of water for space propellant (priced at around $1.74 million/tonne), and contain manufacturing facilities for solar panels or other manufactured goods from mined space materials. At least some humans seem to be lurking in the background but not much information is given on their roles or habitat. The rate of return on investment for the project culminating in 2040 is a respectable 22%. However, we could make some of the same assertions made by Spudis (2014). They employ the Mond process. Their assumed mining and processing equipment seem reasonable but none of these processes have been demonstrated yet. Furthermore, their results rely on optimistic assessments of space manufacturing for around half of their profits in the last year of operation with the remainder coming from water and the sale of PGMs.

Space tourism has often had recent mention as a commercial space activity. However, after Deniz Tito purchased the first tourist flight to the ISS in 2001 from the Russian government for more than 22.5 million 2021 USD, only a few others followed until 2009. Then there was a hiatus until David Branson and Jeff Bezos made suborbital flights in 2021 (Street, 2021). https://www.globenewswire.com/news-release/2022/08/30/2506432/0/en/Global-Space-Tourism-Market-Report-2022-Expansion-of-Sector-

Bodes-Well-for-General-Space-and-Technology-Research.html estimates the global space tourist market might reach 8.67 billion USD by 2030. Still quite small by earthly standards. Statista estimates the pre-covid global tourist industry at more than 9 trillion dollars in 2019 (Statista Research Department, 2022), which equals more than 10% of estimated global GDP (The World Bank, 2022) that year. The question is how much of this cyclic industry can the space market tap into.

Capova (2016) also mentions some other intriguing potential commercial space ventures: memorial space flights, she calls exo-burials, and extraterrestrial marketing (exo-marketing), although she cites no cases of exo-burial, apparently a Doritos commercial broadcast towards the Big Dipper in 2008 has the Guinness Record for first space advertising. Planetary resources sold space selfies to fund an orbiting space telescope (ARKYD 100) that would allow purchasers to have their pictures sent into Space with Earth in the background. Insufficient funding caused the program to be cancelled with the money refunded (Cade, 2016). While Hackl (2020), which contains some other historical examples of government agencies selling advertising opportunities, sites a few other examples.

Martínez, Moyano-Cambero, Trigo-Rodríguez, Alonso-Azcárate, and Llorca (2017) agree we do not yet know how to excavate and refine metals in situ with little gravity and atmosphere. Yet they and others are optimistic that successful modifications of existing technology are not too far away. For example, Martínez et al. (2017) and Andrews et al. (2015) suggest a variety of solutions. Push loose surface rubble into a collection bag by a spinning blade. Adapt needed drilling, blasting, cutting and crushing to function in the space environment. Although chemical separation may be difficult at first until the need chemicals can be obtained, magnetic and electrical properties should still work provided we can get the needed energy, and we can keep our outputs from floating away. Martínez et al. (2017) suggest H_2O, CO_2, and hydrocarbons can be recovered by distillation; iron, oxygen, and other metal alloys in silicates can be recovered by electrolysis; and the Mond process reappears to recover nickel (Andrews et al., 2015). Further, iron and nickel can use separated using magnetic properties. Nuclear power and solar are the most often suggested sources for electricity with water to produce the hydrogen and oxygen needed for propulsion. Sonter (1996), who also references earlier O'Neill work, suggests we also might try mass drivers, which would propel the ship with rapidly ejected regolith waste after being separated from the valuable materials. Komerath, Rangedera, and Bennett (2013) have a nice discussion of various possibilities for asteroid mining methods as well as other needed technology especially related to robotic mining. Anthony and Emami (2018) also have discussed the technology of asteroid mining methods and include a section on the technology of propulsion storage.

Many studies now seem to agree that water used in space as fuel for space travel and eventually for other uses will be one of our first mining target. Spudis (2014) argues that water is not in free form in NEAs. Rather it is chemically bound in phyllosilicates (clays) and will requires temperatures in excess of 500 °C to recover. At those temperatures water will be prone to rapidly recombine with other common minerals in the clays. This suggests a low water yield for a high input of energy. However, current thoughts are that the moon now contains fairly significant quantities of water ice and will be a near term water target. As our techniques improve the prospects for water mining on NEAs will improve. The main asteroid belt beyond the frost zone also contains copious amounts of free water in the form of ice, which could be a target if space colonization moves further out.

Hein, Matheson, et al. (2020) note that none of the suggested water recovery techniques have been tested in space, but many seem to think this is a fairly surmountable problem. (Dreyer et al., 2016) laboratory tests find that concentrated sunlight will break carbonaceous chondrite asteroid material and release volatiles such as water. They argue this could be applied by trapping excavated asteroid material in inflatable bags and irradiating it with concentrated sunlight. Calla, Fries, and Welch (2019) argue for mining water asteroids using multiple small crafts (< 500 kg each for delivery of 100 kg of water). They note 10 different asteroid water mining technologies and show their pros and cons based on scalability complexity, technical feasibility, and durability in their table 1. They select microwave drying and vapor collection as best for their small craft missions to return water to a convenient orbit for space fuel depots. The do find some missions that break even after 10 years with 200 mining spacecraft or after around 8 years with 400 mining spacecraft returning water to cislunar space. However, their break evens do not seem to include a rate of return and their price of water is assumed equal to the launch cost from Earth of around $38,700,000 per tonne (2021 USD).

Hein, Matheson, et al. (2020) also consider multiple missions but with even smaller craft than Calla et al. (2019). With their 150 kg dry mass ships, they return water to cislunar orbit with water priced at about $22.1 million per tonne (2021 USD). For missions that also return platinum to Earth at about $33.2 million per tonne (2021 USD), they manufacture heat shields in situ on the asteroid and increase the dry mass of the spacecraft by tenfold. They do make adjustments for lowering Earth's price with platinum entering the Earth's market. They use solar sails to return the cargo to save on fuel cost with a mission with return less than 10 years. With no rate of return included, they find water breaks even for most cases but platinum only breaks even under rather unrealistic assumptions. Their results with no rate of return, are hardly an endorsement for asteroid mining of water, let alone for platinum mining.

Rare earths along with PGMs are also mentioned as potential targets for return to Earth from asteroids. However, evidence is weak that asteroids are well endowed with REEs. Nakamura (174) analyzed samples from a number of ordinary chondrite and carbonaceous chondrite meteors and found their concentration lower than in Earth's crust. Lewis (2016) also questions their feasible and claims asteroids tend to have little REEs. Martínez et al. (2017) study the composition of carbonaceous chondrite asteroids, often cited as promising targets for mining for use in space because of their water and metal content. They cite studies that compare REE concentrations on carbonaceous chondrite asteroids to the concentrations on the Earth's crust and also find them to be lower.

Rare earth elements are not so rare on Earth, but they typically travel together and are too similar to be easily separated (Long, Gosen, Foley, and Cordier, 2010). REE ores vary considerably. It can take multiple chemical processes tailored to unique ores to separate REEs into separate elements and to remove radioactive elements such as thorium (Krishnamurthy and Gupta, 2016). Given the difficulties in separating rare earths on Earth, they do not expect REE metals to be mined from asteroids for return to Earth.

Royal Astronomical Society (2019) argues there is stronger evidence of REEs on the moon. Gamma spectroscopy suggests thorium deposits on the moon and the REEs often accompany thorium as does uranium. However, there is still the problem that they are very complicated to process on Earth and would be even harder to process in space.

Helium-3 is another isotope that is often cited as a mining target on the moon for use as a fuel in fusion reactions. Because the moon does not have a magnetic field to deflect helium-3 thrown off by the sun, but has enough gravity to hold helium-3 that bombards it, helium-3 is more abundant on the moon than on the Earth or NEAs. In the very hot temperatures on the sun, light isotopes of hydrogen fuse together into helium and generate a great deal of energy. Helium-3 can also be used a fuel in such reactions. However, commercial use of fusion is not with us just yet. There have been dreams of using such fusion as an unlimited source of energy since the first successful laser generated reaction was accomplished back in the 1970's. However, it was only in late 2021 that a positive net energy balance was accomplished. That is more energy was generated from the reaction than it took to get the reaction going (Starr, 2021). Royal Astronomical Society (2019) also argues against counting on helium 3 as the concentrations are so low.
Besides the flow of costs and income over the life of the mining venture, we need to know the discount rate to compute NPV in equations (3) and (4). The NPV for a project is quite sensitive to the discount rate for long term projects. For example, a project that costs 5 to develop takes 10 years to build with cost divided equally at the beginning of the 10 years before yielding revenues starting at the beginning of year 11 with an after tax profit if 1 paid at each year of production for 40 years is worth 6.48, 0.39, -1.24, -1.70, and -1.80, if the discount rate is equal to 5%, 10%, 15%, 20%, and 25%, respectively.

https://minevaluation.com/wp-content/uploads/2016/02/CollinsEllis_DiscountRateCaseStudy_SME2013.ppt.pdf notes that one way of estimating a discount rates is the sum up the components of the discount rate, which starts with the risk-free rate (typically a government security of equal maturity to the project.) For example, the interest rate of 30 year U.S Treasury Securities on September 2, 2022 was 3.35%. (https://ycharts.com/indicators/30_year_treasury_rate) To this risk free rate is added all the risks premiums, which include the overall market risk premium (relating to overall economic health of the economies related to the operation, the company size premium (usually large companies face less risk), industry risk, and site specific risk (https://minevaluation.com/wp-content/uploads/2016/02/CollinsEllis_DiscountRateCaseStudy_SME2013.ppt.pdf.

The discount rate to use in equations (3) and (4) could be quite high given the riskiness of new Space ventures. https://minewiki.engineering.queensu.ca/mediawiki/index.php/Discount_rate suggest that discount rates on Earth for mining ventures typically lay between 5 and 15%, but can be higher for very risky projects. https://insights.csaglobal.com/market-value-doesnt-match-npv/ cite examples of three feasibility studies on Earth mining project that use a post-tax discount rate of 8%. Some commercial mining projects estimates for space mining have used discount rates within the 5%-15% range suggested above. For example, (Hein, Matheson, et al., 2020) use a rate of 10% for mission to mine asteroids to return platinum to Earth. However, more have suggested higher rates. Sonter (1996) surveys the literature and suggests that space mining of asteroids would require discount rates of 20% to 25%. (Andrews et al., 2015) concur and imply the discount rate needs to be at least 20% for space mining ventures to acquire funding, while (Sommariva, 2015) uses rates of 15% and 20% on asteroid mining simulations for mining of precious metals for earth return including mining of water for fuel used for transport back to LEO. SGC20 (Sommariva, Gori, Chizzolini, and Pianorsi, 2020) consider mining the moon for water based rocket fuel using a discount rate of 17%, while (Carver et al., 2020) consider mining deep sea modules (also considered risky ventures) for nickel, cobalt, copper, and manganese using rates from 15% to 25%.

The above examples suggest that the risk premium for commercial mining in Space might be 10% or even higher than for mining on Earth. So what are some of these risks. Clearly there are the technical risks already mentioned earlier. Although we likely have the capability to mine the Moon and other nearby objects, we are still not certain just how we will do so. However, even if we are able to mine in Space, it is not yet clear we will want to do it in the near term. In equations (3) and (4) there is considerable uncertainty and likely variability in the cost and prices.

https://home.kpmg/xx/en/home/insights/2021/02/risks-and-opportunities-for-mining.html cite a variety of risks for mining on earth including "environmental risks including new regulations", "commodity price risk", "permitting risk", "economic downturn/uncertainty", "access to capital including liquidity", "community relations and social license to operate", "political instability", "global trade war", and "regulatory compliance changes".

"Community relations and social license" to operate may not crop up at the mine and processing sites so soon as most mining operations are likely to be uninhabitated areas. But the shared heritage provision in international treaties, mentioned later, may prove to be a contentious issue if the fruits of mining are required to be shared. Many of the other risks will be encountered in space. Under environmental risks, we can include the dangers of working in space. Mining on earth is a rather dangerous occupation. https://www.howden.com/en-us/articles/mining/we-need-to-talk-about-mining" indicates that the global mining labor force suffers 8% of fatal accidents, but only accounts for 1% of the labor force. Space mining if done with human is likely to be considerably more dangerous. Some of the culprits they mention extreme temperatures, explosions, and toxic air are all possibilities in Space. Not to mention the health effects of low or no gravity environments and potential isolation of being far from home.

Conducted robotically, with new and complicated technologies, accidents are always likely events that will influence cost. Takeoffs at supersonic speeds with highly explosive fuels can clearly provide some risks as well. Commercialization of earth air travel started out with a variety of accidents. Figure 13 shows the number of fatal hull loss accidents by type of transport. These are accidents where the plane was non-salvageable with some loss of life. Over the roughly 70 years shown, the trend has been down for these major four types of flights. The improvement has been steeper for commercial passenger flights than for charters and freight.

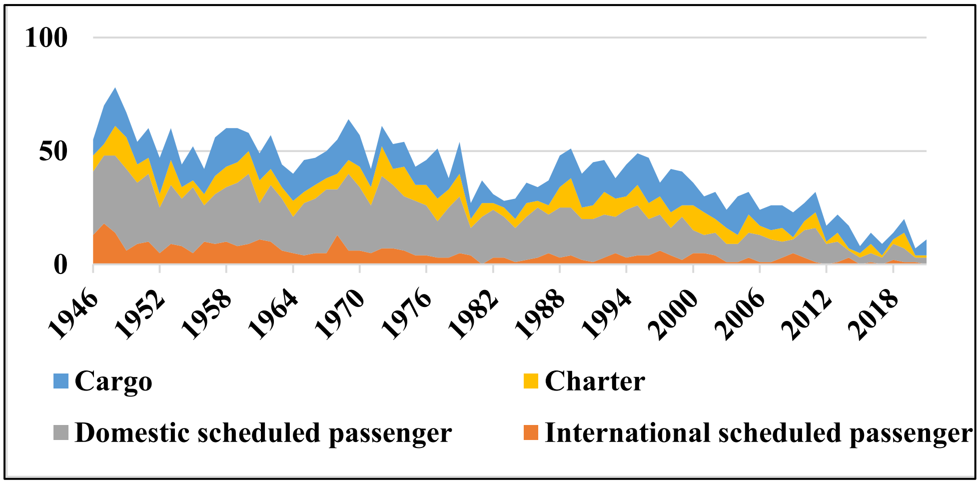
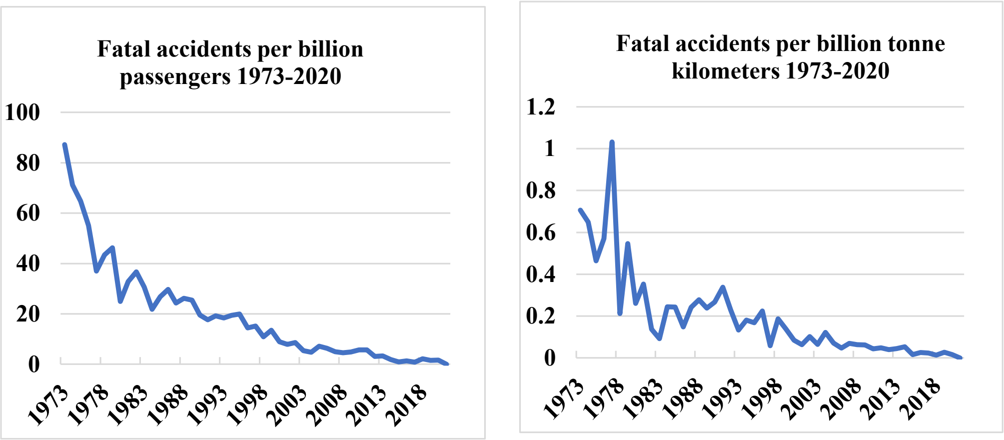


Figure 13: Fatal Accidents by Flight Type 1946-2021

Source: Created from data at https://aviation-safety.net/statistics/nature/stats.php.

Notes: Includes military and corporate air accidents.

If we control for activity as in Figure 14, the record is even more impressive. Thus, we can expect that safety for space travel and mining will improve over time, but danger starts at a higher level and it may take many decades to accomplish the improvements.


Fatal accidents per billion passengers 1973-2020

Fatal accidents per billion tonne kilometers 1973-2020

Figure 14: Fatal Accidents per activity 1973-2020

Source: Created from data used in Figure 13, https://data.worldbank.org/indicator/IS.AIR.PSGR, and https://data.worldbank.org/indicator/IS.AIR.GOOD.MT.K1

https://www.popularmechanics.com/flight/g73/the-most-famous-airplane-crashes/ discusses 13 prominent air travel accidents from 1956 to 2019 and indicates the responses to them from both the government and private sector that improved safety including. Governments made improvements in air traffic control and increased regulatory requirements for more safety controls including smoke detectors, fire resistant materials, automatic sprinkler systems in cargo holes, equipment for real-time tracking of commercial planes and enhanced inspection and maintenance requirements. Private companies also made improvements including better pilot training and equipment improvements.

As of yet, it is not clear what the regulations for space mining will be. Thus, space miners are likely to face "regulatory compliance change risk" as well as the tension across international jurisdictions. If international maritime law and enforcement are any indication, we have not really mastered the implementation of law and order on the high seas as witnessed in (Urbina, 2019), where fishing boat crews are routinely enslaved, environmental laws are flouted, pirates often steal with impunity and murders go unreported. Off-world mining may face some of these same issues, and we see often see this wild west ethos in the imaginations of science fiction writers.

"Permitting risk" and "political instability" are also relate to the functioning of government and the international legal and regulatory framework needed for commercial activities. Companies will need to comply with both national and international laws but may be hesitant if those laws do not exist, are ambiguous, or are contradictory. So far there are only a few national space laws that relate directly to mining. In the U.S. law passed in 2015 and Luxembourg law passed in 2017 the law of capture prevails. In the two existing laws. It is not clear that these laws are consistent with international space law. The UAE law passed in 2020 is a bit more circumspect with promotion, regulation, and permitting of space activities. It is silent on the law of capture indicating that the permits indicate the terms of the activities permitted. Lee (2012) suggests such legal risks relate to unclear property rights relating to the mining operations, extracted material, and any intellectual property rights; any ambiguities, potential delays, or other surprises in obtaining needed government approval and permits; and any ambiguities in liability and contractual enforcement. Legal frameworks providing clarity on these issues are not yet very mature. At the international level there are six relevant international treaties that will pertain. The first is the nuclear test ban treaty banning nuclear explosions in the Earth's atmosphere, outer Space and under the sea entering into force in 1963. Prior to the ban, the U.S. Atomic Energy Commission had an active research program for nuclear mining on Earth. Given the large amount of energy contained in nuclear fission reactions (0.4 kg of uranium equals the energy of about 8000 tonnes of TNT), its use could reduce the needed mass sent up from Earth. However, this treaty and likely public protest precludes nuclear blasting as a mining method in Space for the near future (Hartman and Mutmansky, 2002).

The second treaty more directly focused on space is popularly called the UN Outer Space Treaty (United Nations, 1966) and entered into force in 1967 (United Nations Office for Disarmament Affairs, 1967). When it was drafted, space mining was not really being considered. It designates celestial bodies to be only used for peaceful purposes and that all such bodies are common property with no entity owning them. The treaty neither allows nor disallows space mining so does not provide clarity on property right issues (Greenspon, 2016). Given the high degree of uncertainty on space travel, technology, and use, the drafters did not draft a more comprehensive legal as was done in the 1982 Convention on the Law of the Sea, but include review clauses for possible subsequent revisions. Another unique feature of the treaty was allowing all states not just U. N. members and also international agencies, such as the European Space Agency, to accept the treaty (Lee, 2012).

Shortly thereafter the third U.N. treaty (the rescue agreement) called on signatories to help each other rescue and return endangered astronauts to the launching states as well as provide any requested assistance to return space objects landing in the non-launching states territory. This treaty came into force in 1968 but does not indicate who will bear the costs of any rescue missions (United Nations Office for Outer Space Affairs, 1967).

The fourth multi-lateral treaty, the 1972 U.N. "Convention on the International Liability for Damage Caused by Space Objects" ascribes liability to launching states for space objects causing damage on Earth, in outer Space, and to aircraft on Earth. This liabilities agreement entered into force in 1972 and currently has 75 participants (United Nations, 2022)). Lee (2012) notes the following ambiguities in the treaty. It does not define airspace, outer space, or launching state. This law would most likely apply initially to the launch and returning vessels to Earth. The fifth multilateral space treaty relates to the registration of objects launched into Space which came into force in 1976. It had 79 participants as of Feb. 2022 https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/registration-convention.html

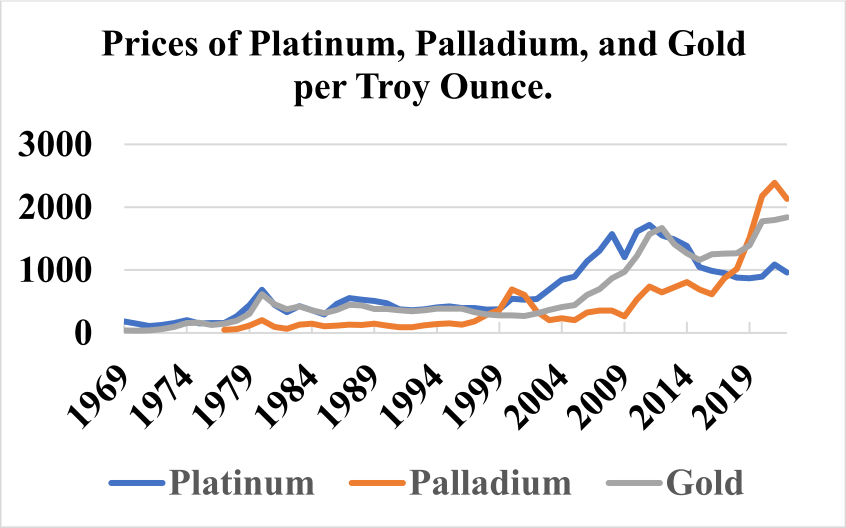
The U.N. 1979 Agreement Governing the Activities of States on the Moon and Other Celestial Bodies effective 1984 more specifically targets the moon and is often called the moon agreement. It stipulated the Moon and its resources are to be used for peaceful purposes as a common heritage of all humankind. There is to be no private or state ownership and no weapons or military bases allowed. Interestingly, the only countries that have soft landed a craft on the moon Russia, first landing Luna 9, 1966, U.S. first landing Surveyor I, 1966, and China (Chang'e 3, first landing 2013) have not ratified the agreement. Nor have Japan or India both significant space faring nations signed on, leaving the treaty's authority over the Moon rather questionable (Froehlich, 2018).

In addition, the U.N. has made a number of statements of principle, resolutions, and guidelines that relate to Space. These are not binding unless they are already covered by other international treaties but may later become enshrined in treaties. They include the 1963 principles that evolved into the international space law; the 1982 principles relating to international satellite television broadcasting; the 1986 principles on remote sensing from Space, the 1986 principles of nuclear power in Space, the 1996 declaration on explorations and use of outer space for the benefit of all states with special account of developing countries (United Nations Office for Outer Space Affairs, 1997). Other resolutions and documents include 1961 and 2000 resolutions on international cooperation for peaceful uses of space, 2007 recommendations enhancements on registering space objects, 2009 safety framework for nuclear power applications, 2010 guidelines on space debris, and 2013 recommendations for national space laws (United Nations Office for Outer Space Affairs, 2022b). National governments also have space laws, which can be seen at United Nations Office for Outer Space Affairs (2022a). See Froehlich (2018) for an overview of national space laws by major country, region, and objective.

For those interested, Lee (2012) discusses the relationship between international law and space law as well as the lessons learned from other laws related to national exploitation of an international asset in a harsh environment – the 1961 Law on Antarctica and the 1994 Law of the Sea. The Law of the Sea comes closer to what he feels will be required in a space law, as it does have a regulatory body and is currently issuing exploration permits and can serve as a starting point. He makes other recommendations for a more comprehensive regulatory approach including information disclosure on any nuclear devices in space, safety regulations, and end of life cleanup of operations. Enforcement and dispute settlement mechanisms will need to be developed as well.

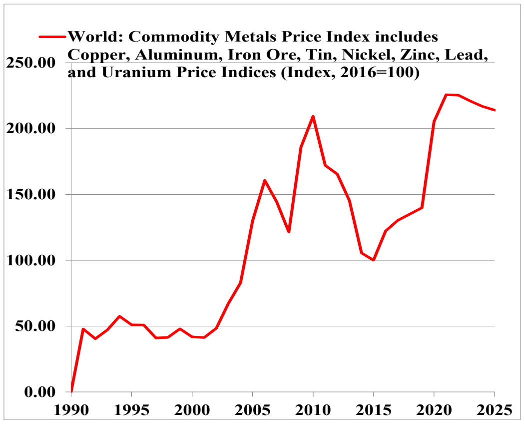
When there are positive externalities in a market, we believe the market will produce less than the optimal amount and we may want the government to step in. To date, governments have led much of the charge into Space. But we expect the private sector to increasingly gain the fore. However, there is likely still a role for governments beside legal and regulatory in the realm of basic science and its contribution to society. For example, government space programs and careers inspire students to choose careers in STEM disciplines (Science, Technology, Engineering and Math). Such programs are helping us better understand the evolution of the Earth, its relation to the solar system as well as climates on Earth and other celestial bodies. We are better prepared to detect and one day deflect Earth threatening asteroids. Further, NASA indicates more than 2000 spinoff benefits related to space research including pollution digesting bacteria and high powered lasers (NASA, n.d.-b).

"Commodity price risk" is certainly likely to be an issue in Space if markets develop as they have on Earth. "Trade wars" and "economic activity" could be contributing factors to price volatility. Figure 15 showing the ups and downs for platinum, palladium, and gold over the years. These high value elements are often cited as potentially being returned to Earth markets.



Source: https:\\www.macrotrends.net.

Most recent studies now argue that basic materials to be used in situ in Space will be our first targets. If the activity in Space remains largely in government hands, this market is likely to remain small. However, if habitation in Space takes off this could be a large market. On Earth we see this same volatility in price in the index for our basic metals.



Source: International Monetary Fund, World Economic Outlook Database, April 2022

"Access to capital including liquidity" is a never ending issue in funding new venture with high uncertainties. On Earth, large mining projects funding may come from consortiums of lenders including banks and development agencies. Will they or venture capitalists be willing to fund large uncertainty projects that are far far away and hard to monitor (Dahl, Forthcoming 2023).

Market structure could also pose a threat. If some of the valuable metals were brought back to Earth, they may face very concentrated markets. For example, South Africa produces a high percent of Earth's PGMs and China dominates the REE markets. With market power, they may be able to lower prices and squeeze out the space miners. Similarly, if miners are selling to distributers with market power, there is risk of hold up with the Earth party refusing to pay an initially agreed upon price. As the space markets mature market power could develop on both sides of the space market and there are, as yet, no competition laws for Space. Thus, we have much uncertainty around a projects environment relating to procurement, contracting, and market structures (Xu, 2020).

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