This document contains Michael Goff's write-up for the environmental Proto-task force for the Overview Roundtable. This research was done in the summer and fall of 2021. Although it was done as part of the Proto-task force, the following represents Michael's thoughts only. Jessica Heim will separately submit her findings.

This document contains the following sections.

- **Environmental Impacts of Space Activity**. We summarize relevant research on the current environmental effects of spaceflight, including ozone depletion, global warming caused by stratospheric emissions, energy usage, and some others.
- **Orbital Debris**. We examine current impacts, possible future Kessler syndrome, methods for mitigating the accumulation and risk of orbital debris, and possibilities for debris removal.
- **Earthbound Environmental Benefits to Space Expansion**. We look at past and possible future benefits of space activity for energy production, food, air, and water recycling, and far future benefits.
- **Energy Options in Space**. My presentation to the Roundtable on 10 November 2021 was based primarily on this material. We consider the possibilities for using solar PV, nuclear fission, in situ resource utilization, nuclear fusion, space-based solar power, and other options.
- **Environmental Ethics**. We review several systems of ethics and some literature on naturalism (or preservationism), population ethics, and the ethics of discounting.
- **Economic Growth**. We review some current growth trends and make a case for economic growth in the context of environmentalism and space expansion. We review the Precautionary Principle and how it pertains to growth.
- **Extraterrestrial Life**. We review the prospects for life in the solar system and the future of the doctrine of planetary protection.

Environmental Impacts of Space Activity

The current space industry, though fledgling, has several environmental impacts, the most significant of which we review below. By far the most significant environmental impact of the ongoing spaceflight revolution will be indirect and far in the future, but it is worthwhile to assess present impacts as well.

Ozone Depletion

The release of certain particles, particularly soot and aluminum oxide, from rocket launches, as well as the reentry of satellites such as from SpaceX's Starlink system, raise concerns about ozone depletion. Several sources, such as this review, identify ozone depletion as the most pressing environmental challenge of current space launch activities.

Precise figures for ozone depletion from space launches are not available, and much of the relevant research is old. The aforementioned review cites several studies, including one from the 1990s that found that 9 Space Shuttle launches and 6 Titan IV launches per year would cause 0.25% reduction in stratospheric ozone. Another study from 1997 found all space launches at the time would result in a 0.025% reduction (there were 87 launches that year and a bit under 100 for most years in the 1990s, compared to 114 launches in 2020).

This paper simulates the ozone loss from an expanded space industry. For 100,000 launches per year, depending on the details of what rocket fuel is used and which ozone simulation is applied, losses range from 0.4 to 1.5 Dobson units (DU). A smaller number of scenarios were run for other numbers of launches; a 0.2 DU loss was found in one scenario for 10,000 launches per year, 3.5-3.9 DU loss for 300,000 launches per year, and 11 DU loss for 1,000,000 launches per year. Extrapolating to the present value of just over 100 launches per year, current ozone loss would be minor. Current stratospheric ozone is about 100 DU.

This paper finds that 1000 launches per year could cause an ozone loss of up to 1%.

According to the Aerospace Corporation, most estimates are that the space launch industry today imposes 0.01% to 0.1% stratospheric ozone loss.

By way of comparison, depletion of stratospheric ozone has been about 60% from 1979—a point at which significant depletion had already occurred—and 1994, the year of the largest ozone hole on record. In recent years, the ozone layer has slowly recovered, as the reduction of ozone-depleting particles mandated by the Montreal Protocol starts to show effect, but full recovery is not expected until late in the 21st century.

The reentry of satellites may also be a concern. About 60 tons of meteoroids enter the Earth's atmosphere each day, and 2.2 tons of defunct satellites will enter when the first generation of SpaceX's Starlink constellation is complete. However, the latter contains much greater amounts of aluminum and may cause greater ozone depletion than the former.

Due to the small size and minuscule impact of the current launch industry, regulation may be premature. But it is important to better understand ozone impact now. In a research program, modeled after the High Speed Research program of the 1990s, NASA could team up with launch providers to better research ozone impacts. Research by the Air Force demonstrates very different emissions of chlorine and alumina across launch systems, and other research suggests that liquid fuels have substantially less ozone depletion potential than solid fuels, suggesting that regulations limiting ozone depletion need not stop launches.

Global Warming

The fuel, as well as embodied energy (the energy required to manufacture the steel and other commodities in rockets) carries its own global warming risk, which is assessed below. Here, we consider the impact of stratospheric emissions on global temperatures.

Global warming can be assessed in terms of additional energy per square meter that is absorbed by the Earth's surface. By way of context, the Intergovernmental Panel on Climate Change maintains four main warming scenarios—RCP (Representative Concentration Pathway) 2.6, RCP 4.5, RCP 6.0, and RCP 8.5—corresponding respectively to 2.6, 4.5, 6.0, and 8.5 additional watts per square meter of radiative energy. RCP 2.6 is a low-end, unlikely scenario for future warming, while RCP 8.5 is also an unlikely, catastrophic scenario. Average total solar irradiance on Earth's surface is about 340 watts per square meter, though this varies greatly by season and climate.

This paper estimates that radiative forcing from present-day (as of 2014) launches is 0.016 +- 0.008 W/m^2, with the 70%, 28%, and 2% resulting from black carbon, alumina, and H_2O emissions respectively. Particles tend to last 3-5 years in the stratosphere. They model the effect of 400 launches per year, a plausible outcome with expanded space tourism and a satellite industry, and find that this will result in a warming of 1°C at the poles, statistically insignificant warming worldwide, and a 5% loss of polar ice.

Modeling the impact of an expanded industry, this paper finds that 100,000 launches per year could result in anywhere from -0.01 to +0.08 W/m^2 of warming. A major factor contributing to warming is water vapor emissions from spacecraft, which stimulates high-altitude cloud formation and traps heat.

While data is limited and highly uncertain, it appears that black carbon and water vapor emissions from launch dwarfs the warming impacts of energy consumption and CO_2 release. We recommend that additional research be carried out, in cooperation with the space industry, and that appropriate emissions regulations can be made when the industry becomes large enough to have a substantial impact on the climate.

Energy and Carbon Dioxide

Energy and CO_2 emissions resulting from energy consumption are estimated as follows.

For energy, we assume the same energy-to-payload-mass as the Falcon Heavy rocket. Total fuel consumption is estimated at Spaceflight 101.

Core (X1): 123,570 kg RP-1, 287,430 kg LOX (Liquid oxygen)
Booster (X2): 123,570 kg RP-1, 287,430 kg LOX
Second Stage (X1): 32,300 kg RP-1, 75,200 kg LOX
Total: 403,010 kg RP-1, 937,490 kg LOX

To estimate the energy content of the RP-1, we start with a calorific value of 12.8 kWh/kg (46.08 MJ/kg) of kerosene. Deep in the bowels of the Department of Energy's building codes are figures on the primary energy content of various fuels. For most petroleum-derived fuels it is 1.05, so that is what we use for kerosene.

For liquid oxygen, this paper estimates that it requires 0.8 kWh/kg, or 2.88 MJ/kg, electricity to make it. Based on the same building code reference above, electricity has a primary energy factor of 3.167, accounting for thermodynamic inefficiency in the power plant and line losses (this figure may be too high in my opinion, but we'll go with it).

We calculate the following energy contents of fuel:

RP-1: 48.384 MJ/kg
LOX: 9.121 MJ/kg

We conclude that the primary energy content of the fuel and oxidizer of a fully loaded Falcon Heavy is about 28.05 terajoules (TJ).

The Falcon Heavy is capable of delivering the following payloads:

To Low-Earth Orbit: 54,400 kg
Geosynchronous Transfer Orbit: 22,200 kg
Mars: 13,600 kg

And so we derive the following energy figures per kg of payload.

To low-Earth orbit: 515.6 MJ/kg payload.
Geosynchronous Transfer Orbit: 1263.5 MJ/kg
Mars: 2062.5 MJ/kg

Based on Ed Kyle's spreadsheet, the following payloads were delivered in 2020.

Low-Earth-Orbit (including elliptical orbits): 397 tons
GTO (including Medium Earth Orbit): 71 tons
Earth-Escape and Trans Lunar Injection: 20 tons

Note that mass is not given for all launches, so the above figures are almost certainly an underestimate.

Ascribing to these three destinations the Falcon Heavy's per-kg energy to LEO, GTO, and Mars respectively, we find that about 336 TJ of energy was expended in 2020.

Aside from the fact that we are missing some tonnage figures, we note that heavy vehicles typically have better fuel efficiency than comparable light vehicles. As the Falcon Heavy is one of the heavier vehicles (by tonnage of payload delivered) in operation, this is another reason why the 336 TJ may be an underestimate.

World primary energy is estimated at 556.63 exajoules in 2020. Therefore, the fuel for space launch constituted less than one part in a million of humanity's total energy budget. CO_2 emissions from energy were 31983 million tons.

There are different fuels that can be used for space launch. RP-1 is a form of kerosene, and we treated it as such for calculations above. Other possible fuels include alcohol, hydrazine and derivatives, liquid hydrogen, and methane. These can either be derived from fossil fuels or synthesized by low carbon processes. Due to the variance and difficulty of developing a uniform estimate, we assume that the carbon intensity (CO_2 emissions per unit energy) of rocket launch is the same as for world energy as a whole. We derive total emissions of about 19,305 tons CO_2. This is equivalent to the annual emissions of 1430 average Americans, the population of a small town. If our simplifying assumptions cause us to underestimate the space industry's energy consumption and emissions by an order of magnitude, the value is still negligible compared to other human activities.

Embodied emissions are the greenhouse gas emissions that result from the creation of a device, separately from what is required to fuel it. For forms of transportation such as cars and airplanes, embodied emissions are typically less than half of the emissions from fuel. We do not have reliable figures for embodied energy of rockets specifically, but we expect that they are significantly higher, relative to fuel consumed, than for other modes of transportation because they are used much less often in their lifetime. Even reusable rockets are typically used dozens of times at most now, while cars and airplanes are used thousands of times. Nevertheless, we expect that even if embodied energy is accounted for, the total energy of space launch will remain negligible.

Other Environmental Impacts

NASA conducted an extensive Environmental Impact Statement on the operation of the Space Shuttle program at Kennedy Space Center. KSC is located at an ecologically sensitive estuary and is host to more federally recognized threatened and endangered species than any other federal facility. Heavy metals and other pollutants were found in the soil just beneath the launch pads, a risk noted in this review as well. Some animals died in the course of Shuttle launches, though no endangered or threatened species were found; fish kills in nearby shallow water as a result of alkalization were observed as well. There was a loss of vegetation near the launch pads. No long-term ecological damage was noted, as some recovery was found in the lull after the Challenger disaster.

NASA also conducted an Environmental Impact Statement for the Mars 2020 mission. A principal concern is the release of radiative material, as the rover uses a MultiMission Radioisotope Thermoelectric Generator (MMRTG). Had the launch failed, there is a risk that people would be exposed to plutonium dioxide and develop cancer as a result. NASA concluded that the maximally exposed person had less than a 1 in a million chance of dying of cancer as a result of the launch, accounting for the probability of launch failure and the risk of cancer in the event of launch failure.

Large satellite constellations, such as SpaceX's Starlink constellation designed to provide Internet access, create streaks of light in the night sky and interfere with astronomy.

Orbital Debris

Orbital debris, also known as space junk, refers to any object in orbit around Earth that does not (anymore) serve a useful function. Although orbital space is vast, high orbital speeds create a growing risk of an orbital collision. It is necessary to take actions to mitigate the problem.

Extent of the Problem

Orbital debris populations are estimated as follows:

10 cm+: 23,000 pieces.
1-10 cm: 500,000 pieces.
1 mm - 1 cm: 100,000,000 pieces.

Of particular concern is a 2007 anti-satellite test (ASAT) conducted by the Chinese military, an event which created 3000 new pieces of debris in low-Earth orbit, or a 25% increase in large objects at the time. The first satellite collision in orbit occurred in 2009 between a Russian Cosmos and an American Iridium satellite, creating at least 2000 pieces of debris at least 10 cm in size. ASAT tests, as well as unplanned explosions, are the largest sources of orbital debris.

Below an altitude of 600 kilometers, a very thin atmosphere induces a drag that causes debris to fall back to Earth in a matter of years. Above 600 km, and especially above 1000 km, debris is of greater concern due to the lack of sufficient drag to cause debris to fall in reasonable time.

Beyond the risk of a complete loss due to collision, such as in the satellite crash noted above, the presence of debris forces satellite operators to install shielding and engage in dodges of large objects. The OECD estimates these actions add 5-10% to the cost of a satellite mission to geosynchronous orbit, and incur a cost in the hundreds of millions of dollars.

Kessler Syndrome

The number of satellites and other objects in Earth orbit, and with it the amount of debris and risk of a collision, continues to grow. In 1978, Donald J. Kessler identified the risk of a cascade, where each collision creates new debris and increases the risk of another collision, such that the process runs out of control. This scenario has come to be known as Kessler Syndrome. The process of a chain reaction of collisions may have already started, albeit at a slow pace, with the 2009 crash.

The prediction market Metaculus estimates (as of August 9, 2021) a 15% probability of Kessler Syndrome by 2050, defined formally as the loss of at least 10% of satellites in one year as a result of collisions with orbital debris. The Inter-Agency Space Debris Coordination Committee estimates that in 200 years, there will be 20-50 “catastrophic” collisions of satellites per year, on the scale of the 2009 collision, though there will also be only a 30% increase in low-earth Orbit debris.

In the worst case, Kessler Syndrome could render key orbital lanes unusable, which would be a major blow to the space industry and could deny humanity access to GPS, weather satellites, and other vital services.

Mitigation

It is necessary to implement measures to slow the rate of growth of orbital debris and insure the safety of satellites and astronauts.

In geosynchronous orbit, satellites should be moved to a graveyard orbit after they reach the end of their useful life. About 80% of satellites comply with this rule. In low-Earth orbit, above 650 km, less than 20% of satellites were deorbited as of 2017. In both cases, compliance is higher with newer satellites. Although deorbiting adds mission cost, greater enforcement of deorbiting regulation may be needed to protect the commons of orbital space.

Graveyard orbits are at a distance, typically at least 200 km, above geosynchronous orbit where satellites and the end of their useful lives can be moved. This action typically requires a delta-v of 11 m/s and three months of propellant, thus subtracting three months from useful operations. Satellites are also emptied of all propellant to minimize the risk of an explosion. Graveyard orbits themselves have limited capacity, and thus this can only be regarded as a temporary solution.

The Space Surveillance Network tracks about 27,000 pieces of debris, mostly greater than 5 cm in size. When a risk of collision is identified with a tracked object, evasive maneuvers can be performed. The International Space Station conducts a maneuver if the probability of a collision is found to be above 1/10,000, regardless of impact on mission objectives. Research is ongoing into ground telescopes and satellites that can tracker smaller pieces of debris.

Spacecraft such as the ISS are equipped with Whipple Shields, which can protect against debris of size up to about 3 millimeters. Unfortunately this leaves a class of objects that are too big to be defended against with Whipple Shields but too small to track.

As orbital space represents a common resource, an orbital use fee, which would be set to a value of about $235,000 per satellite-year, fee has been proposed. According to a model, this would more than quadruple the long-term value of the space industry.

Active Debris Removal

Even if there are no more space launches, or if compliance with disposal protocols could be followed and successful 100% of the time, the amount of space debris is projected to keep growing due to further collisions. Therefore, methods to remove debris, known as Active Debris

Removal (ADR) are necessary. An estimated 5-10 well-chosen objects would have to be removed each year to keep the level of debris stable.

It has been estimated that it would cost $603-622 million per year (2014 dollars) to remove 15 objects per year.

Mark and Kamath review some methods of ADR.

Cooperative Methods: I'm not sure what the authors mean by this.

Laser-Based Methods: Ground-based or space-based lasers are used to sublimate and deorbit pieces of debris. This works best for small pieces. Phillips identifies this method as the most cost-effective, but technological readiness is a challenge.

Ion-Beam Shepherd Based Methods: This method uses ion beams (a beam of quasi-neutral plasma) to impart momentum on orbital debris and deorbit it. IBS would be fairly fast and technically feasible, but energy consumption is an issue.

Tether-Based Methods: Described by Sanmartin et al., this method uses a multikilometer electrodynamic tether to impart momentum on debris. The feasibility of the method is unclear.

Sail-Based Methods: This paper explores the idea of attaching solar sails to debris to deorbit it or move it to a disposal orbit. A challenge is that these methods are slow and hard to control.

Satellite-Based Methods: A microsatellite would use a robotic arm to capture debris. It is described here. These methods tend to be complex.

Unconventional Methods: This is a catch-all term used by the author to describe methods that don't fall into other categories, such as covering debris in expanding foam, micron-scale dust, and other techniques. They are not judged to be technically feasible at this time.

Dynamical Systems-Based Methods: These methods are based on gravitational perturbation by the moon. It's not clear to me how they would work as ADR.

The authors judge tether-based methods and dynamical-systems based methods to have the highest technological readiness levels.

So far, there is no ADR presently going on. The European Space Agency announced the ClearSpace-1 mission, to launch in 2025, to demonstrate ADR. Given the possible severity of the space debris issue and anticipated growth of the spaceflight industry, more missions of this nature would be welcome.

Earthbound Environmental Benefits to Space Expansion

Past ventures in space exploration, such as the Apollo Program and the International Space Station, have brought about significant technological advances that were applied on Earth. While the most efficient short-term path toward environmental improvement does not generally lie in the stars, continued effort into space expansion, including the establishment of self-sufficient habitats, will almost certainly improve earthbound environmental outcomes.

Energy

At present, about 83% of the world's primary energy supply comes from fossil fuels. The share of energy as nuclear power has been slowly decreasing, while the share of renewables, though increasing, is increasing at a rate insufficient for a strong response to climate change. An off-world settlement will necessarily supply its energy from non-fossil sources, most likely solar power in the near term. Other options include the wind energy in the upper clouds of Venus, if Venusian floating habitats can be established, geothermal (areothermal) power on Mars, and nuclear energy. Satellites were an early market for solar photovoltaics, before the technology was viable for commodity electricity generation, and NASA and others are developing small modular reactors for use in space, a technology that may also be an important energy solution on Earth. Much farther are the possibilities of solar power beaming and fusion power, but both would clearly be useful for offworld living and for Earth's environment and general well-being.

Given an abundant, affordable source of clean energy, there are immense possibilities to use it for positive environmental outcomes. At present, most transportation fuel in the world is supplied from refining petroleum. For some applications, such as personal vehicles and trains, direct electrification may be the most practical low-carbon solution. For others, such as long-range trucking, aviation, and transoceanic shipping, electric batteries are of insufficient energy density, and the only way to decarbonize is with low-carbon synthetic fuels. These can be made through electrolysis, with an abundant source of clean power, and a source of carbon dioxide such as the atmosphere (direct air capture) or seawater. At present, these electrofuels are prohibitively expensive. But with the technology very similar to that being developed by SpaceX to synthesize rocket fuel on the surface of Mars, space exploration can be an important catalyst for the development of electrofuels.

Food, Air, and Water

Space habitats need to be very efficient with their use and recycling of air and water. On Earth we are concerned with the buildup of CO_2 and the provision of fresh water. Space exploration can help catalyze direct air capture, which may be necessary to reduce atmospheric CO_2 levels, and water desalination, an inexhaustible source of water in otherwise dry areas.

Land use, primarily for agriculture, is one of the greatest environmental concerns today. With abundant energy, it will be feasible to increase agricultural yields by a factor of dozens or even hundreds, feeding a far larger population on far less land. This can be accomplished with technologies that are available today but are too expensive, mainly due to their energy needs: greenhouses, hydroponics, vertical farming, cellular agriculture, and electrolyzed proteins. The latter options are particularly exciting for their potential to eliminate livestock suffering as well as reduce land use impacts. Agricultural land will presumably be scarce in a space habitat, so the technologies for offworld independent living should catalyze high density, high intensity agriculture.

Far Future Possibilities

Many other examples could be given, such as the environmental potential for advances in robotics, urbanism, and materials science for which space exploration and habitation will be a forcing function, but they will be omitted for consideration of length. But the most exciting possibilities are in the far future.

Once an extraterrestrialization event occurs, or the establishment of a self-sufficient habitat away from Earth, particularly in orbit around Earth or the Sun, then rapid development is likely to follow. Orbital habitats such as O'Neill cylinders, unencumbered by gravity, can trade with each other much more easily than planetary surfaces can trade with other worlds, and they have virtually unlimited room to expand. Orbital habitats are likely to quickly overtake Earth's surface by wealth, and Earth's surface would be depopulated except for a remnant tasked with protecting humanity's cultural heritage. Under most systems of environmental ethics, for people to appropriate asteroids and the surface of barren planets is not without cost, but a much lesser cost than to appropriate the surface of Earth, which is full of complex life.

Finally, though it cannot readily be quantified in terms of tons of CO_2 or hectares of land spared, the value of a wider experience of the overview effect, in terms of raised environmental consciousness, should not be discounted. The Earthrise photograph, captured on December 24, 1968 as part of the Apollo 8 mission, is widely regarded as having been a major contributor to the modern environmental movement.

Energy Options in Space

In this section, we review several options for producing or harvesting energy in space.

Overview

Generating energy in extraterrestrial environments is a critical problem for any human expansion effort. This technical analysis finds that a Mars base would require 90 kWe (kilowatts electric) per person for a 12 person base, 45 kWe/person for 150 people, and 20 kWe/person for "more advanced" projects. Soilleux and Gunn, reviewing several other studies, find per-capita electricity needs of orbital habitats to be 3 kWe/person, 10 kWe/person, or 26.4 kWe/person. On the moon, Koster finds a need of 3 kWe/person for a four person research base, and this survey reports findings ranging from 10-60 kWe/person. The International Space Station requires 17 kWe/person. For energy-intensive terrestrial habitats, Soilleux and Gunn find electricity needs of 6.8 kWe/person for the McMurdo base in Antarctica in the Winter, 30 kWe/person for the Halley VI base in Antarctica, and 88 kWe/person used by Biosphere 2.

By comparison, electricity consumption in the United States (about a third of all primary energy consumption) is about 1.5 kWe/person, and it is about 0.4 kWe/person worldwide.

Off-world citizens would need much more energy-intensive forms of food production and water and air recycling than Earth citizens. Reliability is critical as well, as a power outage would be much more threatening to a vulnerable space habitat than an Earth city.

Solar Photovoltaics

From the 1950s, most satellites use solar photovoltaics to power their operations. Satellites were an important early market for solar PV, at a time when the technology was prohibitively expensive for most terrestrial applications. While solar PV commercialization is widespread and rapidly expanding today, satellites remains at the cutting edge of PV and continue to advance technology that may have terrestrial use, such as multijunction cells, including gallium nitride and silicon carbide cells.

Satellites are useful technology pulls for solar PV, since usable surface area is a scarce and premium commodity. There is a need to develop ever more efficient PV, which has application in reducing land area required on Earth.

Solar PV is the power source for the International Space Station, as well as the proposed Lunar Gateway, and is suggested (along with nuclear power) for lunar bases. Juno, which is conducting scientific missions around Jupiter, is to date the farthest from the Sun that solar PV has been used and the only use of solar PV so far in the outer solar system (this will be exceeded by the Lucy mission to the Jovian trojans). Sojourner, as well as the Mars Exploration Rovers (Spirit and Curiosity) used solar PV, though Mars 2020 uses a radioisotope thermoelectric generator.

Mars receives a bit less than half the solar irradiance of earth. Despite the thin atmosphere, suspended dust settles on solar panels and degrades their performance.

Compared to terrestrial power, cost is less of an issue for power in space, though cheaper multijunction solar panels will further their uptake in space.

Nuclear Power

Following, we review several ways to harvest usable energy from radioactive decay and nuclear fission. The prospects for nuclear fusion are discussed below.

Radioisotope Thermoelectric Generators

Radioisotope Thermoelectric Generators (RTGs) use the heat generated by radioactive decay of a long-lived isotope, commonly Plutonium-238, to generate electricity. RTG-powered spacecraft also can employ radioisotope heater units to keep spacecraft warm in deep space. RTGs have been used in the Mars 2020 mission, the Curiosity rover, and most missions to explore the outer Solar System.

RTGs, and NASA's current generation of multi-mission RTGs (MMRTG) has not so far been the cause of a spacecraft accident or cause detectable health damage. An environmental impact study from the Mars 2020 launch found an acceptable level of risk to human health in the event that the launch had failed and the MMRTG released. A meltdown from an RTG is physically impossible, as there is no controlled fission occurring, but there is still a risk from scattering of radioactive material and exposure. An earlier analysis of the Ulysses mission found that up to 3 cancer deaths worldwide were expected in the event of an accident after launch that scattered the mission's RTG, with upper bounds 10 times higher. Other studies have found launch RTGs and fission reactors to be safe. See also NASA's statement on RTG safety.

Plutonium-238 is a manufactured isotope, not found in meaningful quantities in nature, and procuring sufficient amounts of it is a possible challenge for the use of RTG.

Small Modular Reactors

Nuclear fission could provide greater amounts of power than an RTG and would be useful as a compact power source. For a lunar base, fission, in the form of a small modular reactor (SMR), has the advantage over solar panels that it would not require batteries or other techniques to keep functioning during long lunar nights.

NASA is developing the Kilopower reactor, a 10-kW class of small modular reactor, for use on the Moon and elsewhere. The reactor would be powered by highly enriched uranium.

Under international regulations, a space fission reactor could not be started until it is safely away from the Earth after launch. Therefore, as with RTG, the health risk of radioactive material being scattered in the event of a launch failure should be minimal. However, the foregoing report suggests more formal procedures for launching fission reactors be established and concrete health guidelines be put in place. This paper also suggests risk management procedures specific to reactors be established, as carrying over lessons learned from RTG launch may not be appropriate.

Even though a fission reactor is not supposed to be activated until after a successful launch, there are scenarios under which Kilopower or other reactors could become critical in the event of launch failure.

Under normal operation, shielding should protect astronauts from radiation exposure from a Kilopower reactor. It does not appear that a meltdown is a risk, and we note that meltdowns have not occurred with other SMRs such as on naval ships, though we have limited information.

Kilopower, and previous SMR designs for space, use highly enriched uranium, which poses a risk for proliferation. Nonproliferation procedures would have to be followed to avoid the risk of terrorists gaining hold of nuclear material. Experience by the U.S. Navy, which cannot feasibly used low enriched uranium for reactors on ships, shows that this can be done safely.

Kilopower has a lifespan up to 15 years. We do not know for sure, but suspect that for missions beyond the lifetime of the reactor, new reactors would have to be supplied from Earth. In the longer term, radioactive materials such as uranium and thorium have been found on the Moon, which offers hope of a non-Earth dependent nuclear economy. It is unclear what fissionable materials exists on Mars. It would be feasible for a small Martian base to be dependent on Earth-supplied uranium, but not a large city.

Nuclear Thermal Rockets

A nuclear thermal rocket uses an on-board fission reactor to heat and expel propellant, as an alternative to chemical energy. NTRs might reach an exhaust velocity of 8.3 km/s, compared to 3-4 for chemical fuels. This would allow faster travel times across the Solar System and/or larger payloads to be delivered. The most significant research effort toward an NTR was NERVA, with R&D efforts peaking in the 1960s. No NTR has flown so far. NASA and DARPA are engaging in NTR R&D.

The low thrust-to-weight ratios of NTRs make them problematic for launch from Earth. Additionally, an NTR launch necessarily entails operation of nuclear fission in the atmosphere, which raises many safety and regulatory concerns. The reactors would be used only in the upper stages, when the rocket has already escaped Earth's gravity.

For a trip to Mars, it is estimated that astronauts would receive less radiation on a nuclear thermal rocket compared to conventional chemical rockets, since the benefit of faster travel time would outweigh the radiation from the reactor.

With the reactors not used for launch, we imagine that the safety concerns raised by nuclear thermal rockets would be similar to those from modular reactors, such as Kilopower discussed above. Efforts are ongoing to design reactors that use low enriched uranium, lowering proliferation risk.

Nuclear electric propulsion is another hypothetical design that would convert nuclear energy into electricity, rather than heat that expels propellant directly. Relatedly, there is also a possible economic argument for microwave thermal propulsion and laser thermal propulsion for launch, which could achieve both a high thrust-to-weight ratio and exhaust velocity. Solar thermal propulsion is a promising option for high impulse interplanetary travel but not suitable for launch. All of these options remain hypothetical.

Nuclear Pulse Propulsion

Nuclear pulse propulsion is a hypothetical system that uses nuclear explosions, external to the rocket, as a source of thrust. Project Orion was an early NASA research effort toward NPP, and later efforts include Project Daedalus. NPP is the most advanced and least developed of the nuclear propulsion methods considered here.

The Partial Test Ban Treaty, which forbids nuclear explosions in space, effectively ended Project Orion and other efforts at nuclear pulse propulsion. Should NPP ever be deemed practical, revisions to international law will be required.

Energy Synthesis

Lunar Ice

It is now generally believed that water ice on the surface of the Moon, particularly in the polar regions, is widespread. Beyond its obvious utility in supporting life, water can be split via electrolysis (powered by solar PV, nuclear fission, or other sources) to make rocket fuel. No major technological breakthroughs are required to establish a lunar propellent export facility, and the capital cost has been estimated at $4 billion. Due to the much lower gravity well of the moon, lunar propellent would be extremely useful for powering an Earth orbit, cislunar, and lunar economy, as well as to refuel in low Earth orbit missions to Mars and elsewhere in the Solar System.

Others, such as at the National Space Society, have made the case for lunar ice mining, as well as this study, this study, and this study. By contrast, this study and this study do not find that lunar ice mining for propellant has a good business case, relative to supplying it from Earth. This study, this study, and this study find that the business case for lunar ice mining depends on the application. Generally the case for lunar-, as opposed to earth-source propellent improves when greater amounts of propellent are needed or for longer missions. There is a better case for geosynchronous Earth orbit satellites than low Earth orbit satellites.

Three companies are currently working on lunar ice mining: Masten Space Systems, Lunar Outpost, and Honeybee Robotics.

Asteroid Ice

Near-Earth asteroids are also a possible source of ice. Deposits on asteroids may be more abundant than on the moon, and some analyses (e.g. this and this) indicate that it would be financially feasible. However, it should be remembered that several recent asteroid mining companies have folded, including Planetary Resources and Deep Space Industries.

Mars In-Situ Resource Utilization

The Sabatier process, using Mars' methane-rich atmosphere, is planned for generating fuel for return trips of Starship and for other purposes such as Mars sample returns. The process is an exothermic reaction $CO_2 + H_2 \rightarrow CH_4 + H_2O$ and is already used on the International Space Station, though it is not economically competitive with cheap natural gas on Earth. More work is needed to demonstrate the Sabatier process on Mars and improve the process in general, such as through better catalysts.

Terrestrial Applications

Advances in off-world fuel synthesis will have great applications on Earth. It may not be feasible to directly electrify some modes of transportation, such as intercontinental flights, transoceanic shipping, intercity trucking, and industrial processes such as steelmaking and cement manufacturing, so there is a great need to develop carbon-neutral synthetic fuels to address climate change.

Site-Specific Energy

Venus wind: Several researchers have suggested harvesting wind power on Venus.

Martian areothermal: Mars is mostly geologically inert today, but there may be pockets where geothermal (areothermal) energy can be harvested, which would be of great help to developing cities.

Titan hydrocarbons: Titan, a moon of Saturn, contains enormous lakes of methane, which on Earth is known as natural gas and is a valuable fuel. Oxygen is needed for combustion, and while the presence of oxygen is not known, there may be a subsurface lake, and combustion would be possible if the water is electrolyzed with wind electricity. However, the foregoing study argues that this is impractical.

Solar Power Beaming

One of the most promising long-term energy options on Earth is solar power (space-based solar power, or SBSP), whereby the solar collectors are on satellites in Earth orbit. The collectors would then beam power to a rectanna on Earth. To avoid scattering in the atmosphere, microwaves are typically proposed to transfer power from the satellites to the rectanna. The rectanna would then convert beamed energy into electricity and distribute power into the grid like any other power plant.

The above IEEE article notes that a satellite is typically 80% efficient in converting power to microwaves, and the rectanna is also about 80% efficient in converting back to electricity. Substantial R&D is still needed.

SBSP would be useful for remote applications for which power would otherwise be expensive, such as military installations. Several concerns have been raised about the prospect of accidents or weaponization of solar satellites, but I haven't yet been able to find this discussed in a reliable source.

Such a system would almost certainly be technically feasible, though basic research is still ongoing. A greater question at present is the ultimate cost. Power from natural gas and other sources typically costs around 6¢/kWh. Paul Jaffe estimates that the cost could be anywhere from 0.33¢ to $15.84/kWh. John Mankins estimates a cost from 3-10¢/kWh.

NASA, as well as the Chinese and Japanese space agencies, have R&D programs into SBSP.

In a recent study, NASA identified remote, expensive power applications, in particular mines, as a good first market for SBSP. They determined that launch costs to GEO should be no more than $188/kg. An alternative would be to manufacture solar satellites on the Moon and launch them to GEO.

Solar satellites have also been proposed for lunar missions, Martian missions, and general space applications. Without the atmospheric scattering that would occur on Earth, lasers instead of microwaves might be the best way to transmit power to the lunar surface.

Nuclear Fusion

In contrast to nuclear fission, fusion operate by fusing light atoms and releasing energy. Fusion does not pose the radiation and meltdown risks that fission poses, which should reduce containment costs as well as promoting safety. The limited cost estimates available suggest that the fusion electricity may be cheap.

Pathways Toward Fusion

Though there are many types of reactions that could conceivably provide fusion energy, there are three main ones that are being explored today: deuterium-tritium (D-T), deuterium-Helium-3 (D-He3), and proton-boron (p-B11). D-T fusion operates at the lowest temperature and has the highest energy density, and for these reasons is the most heavily explored route today. However, D-T fusion also yields the highest neutronicity (emission of neutrons from the reaction), which is bad because the flow of neutrons cannot be controlled by magnetic fields, and neutrons tend to cause damage. p-B11 fusion has the lowest neutronicity, lowest energy density, and highest temperature. D-He3 occupies a middle ground on each of these three metrics.

There are many technological paths toward fusion that are proposed. Of them, the most well-developed is the tokamak. The flagship tokamak project is ITER. However, ITER and the follow-up demonstration power plant DEMO will be a long wait, with commercial power plants not to be expected until the 2060s. Inertial confinement fusion, whose flagship endeavor, the National Ignition Facility, recently achieved a milestone toward ignition. Other approaches include magneto-inertial fusion, spherical tokamaks, stellarators, field-reversed configurations, z-pinch, and electrostatic.

Z-pinch fusion is of particular interest for space propulsion, with a possible 35-day one way trip to Mars (compared to the 7 month trips that are common now). Project Icarus is one effort to design fusion rockets capable of interstellar travel. See also this recent overview of the state of z-pinch fusion development.

Availability of Fuel

Deuterium is a stable isotope of hydrogen (with one neutron) and is abundant throughout the inner Solar System. Tritium, a radioactive isotope of hydrogen with two neutrons, is also important for nuclear weapons and needs to be actively produced. Adequate production of tritium in the United States has become a problem. World production of tritium would need to be greatly expanded to accommodate commercial fusion plants using D-T reactions. Within tokamaks, tritium can be bred from lithium; making this cycle self-sufficient is an active area of research.

Boron-11 is a stable isotope of boron and, we believe, should be readily available anywhere in the solar system.

Helium-3 Mining

If fusion from the D-He3 route pans out, access to helium-3, particularly on Earth, could be an issue. There should be enough He3 from terrestrial sources for a small scale deployment of D-He3 reactors.

Aside from possible fusion applications, helium-3 is used now for plutonium detection and medical imaging.

On the Moon, helium-3 accumulates on the surface due solar wind, and the Moon has been proposed as a source of helium-3 for D-He3 reactors on Earth. Such an operation would be extensive. This review finds that it would be profitable only in the best case scenario. No He3 has been recovered from the Moon yet, but several private ventures have tried. Frank Close doubts the idea is realistic, while Harrison Schmidt is a proponent.

Most helium-3 used today is produced through tritium decay. Tritium has a half-life of about 12 years, and He-3 is the main decay product. As tritium is currently in short supply through the scaling back of reactors, so too is He3. It is unclear to us whether, in a future where He3 demand is greatly increased through the use of reactors, mining from the moon will be more economical than tritium breeding.

Helium-3 mining from gas giants, such as Uranus, has also been proposed.

Exotic Options

The concepts outlined here will probably not be feasible on any relevant planning timeline, but they may be possibilities for the far future.

Antimatter

Antimatter is composed of anti-particles, which are similar to regular particles but have the opposite electric charge. When particles and anti-particles come into contact, they annihilate, converting all mass into other forms of energy. In theory, antimatter should be one of the most efficient modes of propulsion under established physics. There are means of storing antimatter, namely Penning traps and Ioffe traps, but they are not yet practical for macroscopic amounts of material. Nevertheless, antimatter does have some current applications, such as positrons (PET, or positron emission tomography) for medical imaging. This presentation offers a general review of production, storage, and other issues.

The amount of antimatter produced today, primarily in particle accelerators, is far less than what would be required for spacecraft propulsion. Produced antimatter is not an energy source, but rather an energy carrier, and a very inefficient one at that. Thunderstorms are a natural source.

Antimatter may be a catalyst for nuclear fission or fusion, in a process known as antimatter-catalyzed nuclear pulse propulsion (ACNP). AIMStar was a project to develop this. In this case, antimatter is not a catalyst in the strictest sense of the word, because it would be consumed in the process, but the traditional nuclear processes would supply the bulk of the energy. See also this paper illustrating how anti-protons can be used to accelerate inertial confinement fusion.

This paper discusses a pure antimatter rocket for propulsion, which could reach half the speed of light. Project Valkyrie was an effort to design such a starship.

Black holes

It may be theoretically possible for the Hawking radiation of a black hole, ejected by parabolic mirrors, to be a source of propulsion. This paper finds black hole propulsion to be at the edge of physical possibility, while this paper does not find it to be doable.

A black hole necessary both to generate sufficient power and be sufficiently long lived would be just under an attometer (10^-18 meters) in size. Assuming that such black holes cannot be found naturally, they would have to be produced, probably through concentrated lasers, and thus black holes would be a (very inefficient) store of energy rather than a source of energy.

Zero-point Energy

Due the Heisenberg Uncertainty Principle, a quantum system even at zero temperature does not have zero energy. The residual motion that must remain is called zero-point energy (ZPE). Zero-point energy is central to a number of major open questions in theoretical physics, and it is hypothesized to be the dark energy that comprises 75% of the universe's mass-energy and drives the accelerating expansion of the universe.

A Casimir effect has been observed experimentally, but it has not yet been shown that it can be harvested for usable energy. Most researchers do not believe that ZPE could be harvested soon, or even in principle. NASA’s Eagleworks Laboratory is conducting research into ZPE. Claims of a functioning ZPE device should be met with extra skepticism due to a history of fraud.

Conclusions

There is no “best” source of energy in space. Solar PV, RTGs, nuclear fission, and ISRU all have their places. Power beaming and fusion are also important for the long term future. The latter two deserve more investment for their potential both in space and on Earth.

There are several safety and others issues that need to be resolved to expand the use of nuclear power in space, particularly fission, and we would like to see more effort put into these issues. However, we see much potential and no show-stoppers.

Environmental Ethics

Systems of Ethics

Within the environmental movement today, the major ethical debate is between anthropocentric environmentalism, which seeks environmental conservation for the benefit of humans, and ecocentric environmentalism, which values nature for its own sake. Animal welfare ethics, though important politically and, to many people, morally, have not been a central animating force of the environmental movement so far. Select environmental ethics are as follows.

Anthropocentrism

Anthropocentrism is an ethical view that the well-being of humans should be the main concern of policy. It is not seriously disputed whether human well-being is important; at debate is whether human well-being is the only thing that is important, or if non-human values should be held for their own sake. W. H. Murdy is one of many proponents of anthropocentrism.

The term anthropocentrism is sometimes used pejoratively, though most governments and mainstream environmentalists implicitly endorse an anthropocentric view when they emphasize the benefits to humans of environmental policy, or the hazards to humans from bad policy.

Weak Anthropocentrism

Weak anthropocentrism is a view that humans and their values should be the central concern of environmental policy. The difference with anthropocentrism, discussed above, is subtle, but the addition of the phrase “and their values” opens the door to the values discussed below to be considered more explicitly, if they emerge as central values from the political process. Hargrove is an exponent of such a view.

Weak anthropocentrism is closely related to pluralism, discussed below, and it may be the most practical framework for a broad set of values to be considered.

Ecocentrism

Ecocentrism is a view best associated with Aldo Leopold and the deep ecology movement. In *A Sand County Almanac*, Leopold stated “*A thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise.”* The emphasis should be understood to be on communities, rather than individual organisms.

Biocentrism

Biocentric ethics center the well-being of individual living organisms. The view is associated, among many others, with Albert Schweitzer and Paul Taylor.

The question “What is life?” is a great challenge for biocentric ethics. There is no consensus today, and it is very likely that discoveries throughout the solar system and galaxy will result in considerable revision in our understanding of life. In philosophy, there is a distinction between natural kinds, or classifications that can be made in accordance with objective criteria, and unnatural kinds, which are inherently artificial and arbitrary. A full understanding of life may fall into the latter category.

Sentiocentrism

Sentiocentrism is an ethical system that centers consciousness as the center of ethical concern. The view is associated with Peter Singer, among others, in his advocacy of animal rights.

As with the nature of life, the nature of consciousness is a well-studied question for which there is no consensus. A sentiocentric view that does not give the same moral weight to all conscious organisms is termed gradual sentiocentrism. For such a view, some measure, such as the number of neurons an organism has, may be used to approximate the moral weight it is accorded. As with life, consciousness may be an unnatural kind.

Aside from environmental concerns, sentiocentric ethics pose dilemmas in areas such as what rights, if any, to afford artificially intelligent agents and the ethics of abortion.

Theocentrism

Theocentrism, often known as Creation Care, is a view moral value derives from creation by God. Hoffman and Sandelands expound the view.

While religious beliefs can be a motivation for environmental stewardship, they are, in the view of critics such as the ecologist Lynn White, the source of anthropocentric views that result in the destruction of nature. Simkins explains the controversy and why an anthropocentric reading of Genesis is not appropriate.

Biotic Ethics

Biotic ethics are the view that the ethical good is the projection of life as far spatially and temporally as possible. Proponents of this view include Michael Mautner and Claudius Gros. Among forms of environmental ethics, biotic ethics may be the system that most explicitly calls for technological advancement and expansion into space.

Other Systems

Technocentrism is a view that places moral weight on technology and views technology as a way to manage and improve the environment. Industrocentrism is an ethical view that places moral weight on industry and regards nature as a source of resources. I would like to consider these views more thoroughly, but so far I have only seen references to them in a pejorative sense.

Pluralism

Pluralism is a philosophical stance that multiple mutually irreducible values should be held simultaneously. See, for example, the work of Bryan Norton (via Afeissa and Mainguy) for an exposition of this view in the context of environmental ethics and its relationship with weak anthropocentrism.

There is no objective criterion, as far as I can tell, to which one can appeal to determine which system(s) of environmental ethics are “correct”. The actual decision will be made in a messy, indeterminate way through the political process and civil society, as ethical decisions have been made in the past. For the purposes of considering space expansion, it may be best to adopt a pluralistic view, or a view that, to the best extent possible, is compatible with every mainstream system of ethics.

The system of ethics has great relevance in determining the best answer to important questions. For example, it remains unknown if there are living organisms on Mars, but it is exceedingly unlikely that there are conscious organisms. Therefore, heavy industrialization on Mars, which would disrupt the local ecology, may be of no concern under sentiocentric ethics, but would be of great concern under biocentrism, if there is life, or ecocentrism, whether or not there is life.

Naturalism

In environmental ethics, there is a concept known as naturalism or, as Martyn Fogg terms it in a specifically spacefaring context, preservationism. This view makes a distinction between humans, as agents, and nonhuman nature as non-agents on which humans act. The ethical claim of naturalism is the preservation of the latter category to the greatest extent possible.

Naturalism is a frequent, though often unstated, assumption behind environmental thought. As Fogg notes, preservationism is unique among strands of environmental ethics in that it inherently proscribes human expansion. While human activity can be an ethical good or an ethical bad under anthropocentrism, ecocentrism, biocentrism, and other ethics, it can only be bad under preservationism. For this reason, we believe it is necessary for space expansion advocates to challenge naturalist or preservationist frameworks.

Naturalism informs ethical stances on several terrestrial questions, such as whether it is ethically good to use assisted evolution in marine conservation, the use of gene drives to eradicate harmful or invasive species, and whether species should be actively relocated in response to loss of habitat under climate change.

The prospect of terraforming Mars remains far in the future, but the possibility raises similar ethical questions. Robert Zubrin makes a pro-terraforming case and rejects a naturalist stance, noting that under any reasonable system of ethics, it would be wrong to sterilize the surface of Earth to resemble Mars, and so it is right to terraform the surface of Mars to look like Earth.

The logical underpinning of naturalism may be an inappropriate dualism between humans and the non-human world, a distinction that will become even more untenable with the advent of extensive tools of transhumanism. In popular parlance, the view that that which is natural must be good is labeled as the “appeal to nature” fallacy.

Population Ethics

Human population is a fraught issue in environmentalism, intersecting with such concerns as resource depletion, competition with non-human values, and economic growth. Independently of these effects, the size of population is an ethical issue with which frameworks such as utilitarianism don’t deal clearly.

Utilitarianism is an ethical framework that calls for maximizing the total happiness of all morally relevant individuals, but the framework is unclear on how many individuals there should be. Within utilitarianism, there is total utilitarianism (totalism), expounded by, for example, Henry Sidgwick in The Methods of Ethics, which holds that the sum of happiness overall individuals is the morally relevant quantity. Opposed to this is average utility (averagism), described for example in Garrett Hardin’s Tragedy of the Commons, which regards average happiness, regardless of the number of individuals, as the morally relevant quantity.

Both of the preceding forms of population ethics carry counterintuitive conclusions and thus are not tenable in their strict form. Totalism results in “The Repugnant Conclusion”, which holds that it is ethically ideal to increase population, even if doing so results in the decrease in average well-being to the point where life is barely worth living. The concept was developed by Derek Parfit, though Tännsjö argues that the Repugnant Conclusion, though unpleasant, should be accepted. Avergism also leads to the questionable conclusion, also described by Parfit, that it is ethically good to painlessly kill people who have a positive quality of life but one below the group average.

Person affecting views also approach the question of how to morally deal with the incommensurability between existence and non-existence. Beckstead et al. outline four PAVs. A strict PAV places no moral weight whatsoever on the question of creating hypothetical lives. A wide PAV makes no distinction between hypothetical future lives and existing lives. A moderate PAV places moral weight on hypothetical lives but less than on actual lives. An asymmetric PAV places negative moral weight on hypothetical lives not worth living but no weight on hypothetical lives worth living.

Since it is not possible to completely rule out the possibility that the creation of life will result in lives not worth living, asymmetric PAVs lead to antinatalist conclusions. Taken to an extreme, David Benatar argues that the ethically sound conclusion is that nonreproduction and the extinction of humanity is the best outcome. Benatar’s views are not widely held, and it is argued that there is no justification for this asymmetry.

Ethics of Discounting

It is common in environmental policy, and indeed in all arenas where decisions must be made about the future, to apply a discount rate. Discounting is the practice of valuing monetary flows in the future at a lower value than in the present, typically around 3-7% per year. However, people living in the future should presumably be given the same moral weight as people in the present. We are thus presented with a paradox.

Discounting is a basic and unavoidable principle in finance. Consider if given the option between being given $100 today or $200 in 50 years. If given the money today, you could invest it, and if you could expect a return of 7% per year over those 50 years, $100 today will grow to nearly $300 in 50 years. Therefore, taking the $100 today is a wiser action.

For example, the social cost of carbon is an attempt to estimate, in monetary terms, the present value of damage done by the carbon dioxide emissions. Most mainstream estimates of the SCC are in the range of $50-100 per ton, though several are both higher and lower than this range (examples here, here, here, and here). However, if no discount rate is applied, then the social cost of carbon has been estimated in the 10s or even 100s of thousands of dollars. See also Rennert and Kingdon for more on the sensitivity of climate damages to discount rates.

Whether humanity achieves a spacefaring breakout could affect an incomprehensible number of lives in the distant future, which in the absence of discounting may make achieving a spacefaring breakout, and the avoidance of existential risks in the meantime, the most important moral considerations.

Conclusion

Ethics place our personal decisions and policies regarding spaceflight on firm intellectual grounds. In our view, formal ethics are shaped by moral intuition and the political process more than the other way around, but we nevertheless regard it as important to develop the ethical frameworks that will allow us to place the case for space expansion on firm ground.

Practical considerations may require us to accept a pluralistic ethical system, whereby questions of what is valued, population ethics, and other questions are informed by a wide range of philosophical concerns, and hopefully solutions can be crafted which are compatible with as many considerations as possible.

However, there are certain views, such as preservationism and asymmetric person-affecting views, which are not compatible with a spacefaring future and which also cannot be well-defended logically. It is important, therefore, for space advocates to challenge these views.

Economic Growth

Space settlement necessarily implies economic growth. While limited crewed missions, such as a return to the Moon or a mission to Mars, can happen today, widespread space expansion and the establishment of independent offworld societies, necessarily entails a substantial increase in technological and industrial capacity. Space settlement, particularly the establishment of independent offworld societies, will also be the cause of enormous growth.

The environmental movement is ambivalent at best toward growth. Within the environmental movement is a degrowth movement, an effort to deliberately shrink the size of GDP, as well as antinatalist and anti-technology movements. Such efforts should be regarded as incompatible with visions of space expansion, and it is incumbent on the space community to offer a more positive vision of growth and of human activity.

Despite the tension, there is some room for common ground. A vision of space expansion could share with the degrowth movement a critique of consumerism. The latter views consumerism as a waste of resources and a cause of environmental degradation without substantial improvement to human well-being. The former should recognize that consumerism is an effect, but not a cause, of economic growth. A social ethic that places more value on hard work, invention, achievement, and family, and less value on consumption and entertainment, would be more conducive to growth.

Growth Trends

It should be keenly remembered that economic growth, societal progress, and advancement into space are neither automatic nor inevitable. Within both the space community and the environmental community, there is a worrying tendency to take growth for granted.

There is evidence that the scientific productivity of researchers is slowing down. Bloom et al. documented the trend and found that in many areas, including Moore's law (the density of transistors on a computer chip), agricultural yields, and life expectancy. Rates of decline of research productivity, which is the amount of scientific progress that should be expected for a single researcher, are found to be 7% per year with semiconductors, 5% per year for seed yields, and 8-10% per year for general productivity across firms. So far this trend has been partially counterbalanced by an increase in the number of researchers. For the economy as a whole, the decline has been more than 5% per year since the 1930s. Our read of the literature is that, while there is much debate on the causes and remedies to declining research productivity, there does not seem to be much dispute that research productivity is indeed decreasing over time.

Related to the slowdown in research productivity is a slowdown in overall economic growth. In recent decades, a long-term slowdown in economic growth has been observed in the United States, Japan, the European Union, and in wealthier countries generally, as economic growth is increasingly concentrated in low-income countries in a process known as the great convergence.

Some countries, such as Japan and Russia, have seen years of sub-replacement birth rates and are now experiencing population decline. The United Nations projects that world population will peak late in the 21st century or early in the 22nd century. A higher population means more people who can be researchers and find ideas, larger markets, and more opportunities for specialization. Therefore, most researchers (see this, this, this, this, this, this for examples) expect that a population slowdown will be a drag on growth.

Rising debt levels are a drag on growth, as higher debt means that governments and businesses need to spend more on debt service, leaving less investment for research, infrastructure, and other growth-enhancing activities. The debt-to-GDP ratio in the United States is now higher than at any point in history except briefly during World War II, and is expected to keep increasing. World debt in general, including government, business, and individual, is increasing.

The factors described above by no means preclude the possibility of a spacefaring breakout, but taken together, they comprise formidable headwinds that should be taken seriously.

A Case For Growth

A case for growth rests on two pillars. First, growth would continue to improve human well-being. The Easterlin Paradox holds that well-being does not improve after a certain income level. However, several other studies, such as by Kahneman and Deaton, Stephenson and Wolfers, Diener, Tay, and Oishi, and Veenhoven and Vergunst, find that higher income induces a higher sense of well-being for as high of levels of income that they can measure. Beyond the life satisfaction index that Easterlin uses and other measures of subjective well-being, growth brings about improvements in well-being that are harder to dispute, such as medical capacity.

The second pillar relates to the tradeoff between human well-being and other environmental measures. There is not a strict zero-sum tradeoff between the two, but with scientific advancement, it is possible to make a positive sum tradeoff. The transition from traditional bioenergy to fossil fuels, and now from fossil fuels to nuclear power and renewables, allow far lesser environmental impact for each unit of value created. The same is true of transitions from whale oil to incandescent lighting to compact fluorescents to LEDs. The world has seen and continues to see steady improvements in energy efficiency, crop yields, water efficiency, and many other areas, which let us do more with less.

Far from a story of relentless growing environmental impact, there are signs of environmental Kuznets curves, which are situations of environmental impacts that grow to a certain point, then decrease as improved technology and efficiency become more important than increased demand. The emission of ozone-depleting substances, sulphur dioxide, carbon monoxide, VOCs, and nitrogen oxide in the OECD (a group of wealthier countries), mercury pollution, and world forestry land, land for permanent meadows and pastures, and cropland have all decreased, though the peak of each land use metric is recent and still not certain.

To be sure, there are important areas for which overall impacts continue to increase, such as greenhouse gas emissions, nitrogen fertilizer use, municipal solid waste generation, and lead pollution. These are areas for continued technological innovation and better policy.

Under biotic ethics, a spacefaring civilization will have the potential to create positive value through terraforming, not merely reduce negative impacts.

Risk Management

In environmental discourse, the precautionary principle is the idea that, in the face of uncertainty of the impact of an action, it is better to avoid the action if there is a risk of irreparable harm. The principle has been invoked against several industrial activities, such as deep sea mining [give some other examples] and carries legal force in some jurisdictions. In environmental ethics, the PP holds, for example, that when it is uncertain whether an entity is sentient, it is better to assume that it is. In the context of space exploration, the PP is applied in the context of the existence of extraterrestrial life: even when the probability is low, if uncertain, it is better to assume the existence of extraterrestrial life and that, if such life comes into contact with terrestrial life, great harm could come to both of them.

In moderation, the PP is a sensible guide to policy. Some modern technologies, such as nuclear weapons and gene editing, are potentially dangerous, and the danger may continue to grow as artificial intelligence and nanotechnology develop. Caution is needed in these cases.

But taken to extremes, the PP is not a sensible approach. The biggest problem is that, when faced with multiple options, there is almost never a risk-free option. The PP may be invoked against nuclear power, for instance, on the grounds that nuclear power plants carry accident and proliferation risks. And indeed this is true. However, history has shown that when prohibitions against nuclear power exist, fossil plants are usually built instead, which carry known hazards of air pollution and climate change. At an extreme level, the PP can also introduce perverse incentives, such as opposition to research that would reduce the level of uncertainty.

A reasonable approach to the PP would blend expected value reasoning with risk aversion, where the probability of a loss is given more weight than an equal probability of an equal gain, but to a finite degree to allow a reasonable level of risk taking. The exact value of “reasonable” is a political and business decision that would be made on a case-by-case basis. In the face of uncertainty, opponents of an activity, not just proponents, must accept some burden of proof for their case, with the burden growing as time goes on. Opponents should also not be permitted to obstruct research that would reduce uncertainty.

Extraterrestrial Life

In this document we consider several questions that are raised by the possible existence of life beyond earth.

Existence of Life

At present, there is no solid evidence of life anywhere in the Solar System, or indeed the universe, except Earth. If life exists in the Solar System beyond Earth, it is almost certainly microbial life, while the existence of more complex life, even civilization, in other star systems is a possibility.

The Committee on Space Research (COSPAR) implements the Outer Space Treaty provisions on Planetary Protection. COSPAR identifies Mars, Europa (a moon of Jupiter), and Enceladus (a moon of Saturn) as the most sensitive spots in the Solar System for the existence of life. Other candidate homes of life are the clouds of Venus, Titan, Ganymede, and Callisto. Mars is of the greatest interest as both a place of high likelihood of life and high likelihood of a near-term human visit.

Although there is no direct evidence, several researchers have made a case for there being life on Mars (see here and here), and even if there is none today, conditions for life may have been more conducive in the distant past. However, life resembling Earth life would face formidable obstacles: cosmic radiation, the lack of plate tectonics, the lack of liquid water on the surface, the presence of toxic perchlorates on the surface, and other problems, so if life exists at all, it may be beneath the surface. Life on Mars, or elsewhere in the Solar System, may have radically different biochemistry than Earth life.

Planetary Protection

Planetary protection is a practice to prevent the spread of life between different planetary objects. The current PP regime seeks to prevent two risks: forward contamination is the possibility of Earth life taking hold on another planet, while backward contamination is the possibility of life on another planet taking hold on Earth. COSPAR seeks to reduce the probability of forward contamination to less than 1/10,000.

COSPAR is designed with primarily anthropocentric considerations in mind: it seeks to avoid the kind of contamination that would interfere with scientific missions. Ecocentric or biocentric considerations, namely to protect any indigenous life that may exist, are not explicit. The Moon Treaty has more explicit ecocentric provisions, but it is not in force among currently spacefaring nations.

The Long-Term Viability of Planetary Protection

The Precautionary Principle, which holds that amidst uncertainty of the risk of planetary contamination, a cautious stance is in order, is sensible today, but it is not a viable strategy for the long term.

Planetary protection regulations have added an estimated 10% to the cost of space missions, with an unquantified cost in terms of what valuable missions could not be done. Delay or prevention of human space expansion is also risky, and rules that increase cost run this risk. Such rules should be placed with care.

Furthermore, as the above source notes, when they exist, planetary protection procedures are not always followed. Procedures existed for the Apollo 11 astronauts to quarantine upon splashdown, but those procedures were deemed unworkable due to rough waves and not followed. Had the capsule brought back harmful microorganisms from the Moon, they might have escaped.

COSPAR's standards to prevent forward contamination are unworkable for a crewed mission. Humans cannot survive the kind of sterilization required of spacecraft. Both China and the United States planned crewed missions to Mars in 2033, rendering the avoidance of forward contamination moot beyond that date if these missions are successful and on time.

We are frustrated by the lack of numerical assessment of the risk of contamination. The probability that life exists on Mars or elsewhere in the Solar System, the risk of forward or backward contamination, and the extent that life would spread if it gains a foothold in another world are all quantities for which we have been unable to find reasonable estimates. If even just a guess, quantitative figures are necessary to inform wise policy. [Perhaps such estimates exist and I am not aware; I would greatly appreciate knowing if this is the case.]

Finally, astrobiological research should be carried out with some urgency. It is neither feasible or ethical to hold back crewed space exploration indefinitely, and since we cannot yet rule out a reasonable probability that crewed exploration will spread life widely throughout the Solar System, there may be a limited window during which astrobiologists can work with pristine environments.