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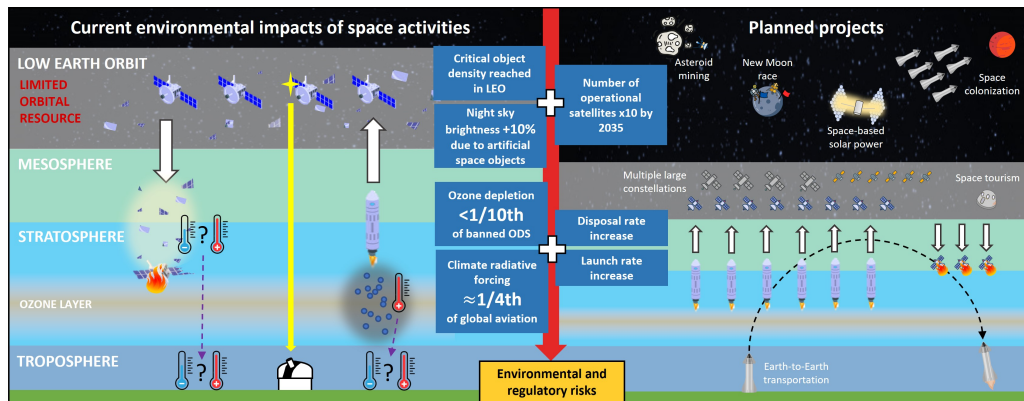
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Graphical Abstract

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Highlights

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- Impacts of space activities on the Earth and orbital environments are reviewed
- Planned projects threaten space sustainability and could attract regulatory attention
- The growth of the space sector is constrained by environmental limits
- Generalizing ecodesign practices would help mitigate the associated risks
- Energy and material intensive plans will be challenged by the ecological transition

Environmental limits to the space sector's growth

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Abstract

Space activities are now expanding at a fast pace and various ambitious projects have been proposed for the future, raising the question of their environmental sustainability. While the space debris situation has been widely recognized as a serious threat to space sustainability, other pressing environmental issues have received little attention yet, although they pose risks to the environment and actors of the space sector. Therefore, this paper first reviews the major environmental impacts of space activities and their potential growth, analyzed together in a comprehensive approach for the first time. The degradation of the orbital environment with space debris has already reached a threshold leading to a future increase of the number of objects even without additional launches, while the contribution of artificial space objects to night sky brightness may have already crossed the light pollution threshold defined by astronomers. Planned large constellations will likely deteriorate the situation significantly. In this context, the formulation of these thresholds within the planetary boundaries framework is proposed to support awareness-raising and policy-making. Furthermore, stratospheric ozone depletion and climate change resulting from rocket emissions could reach levels triggering regulatory responses in the next decades due to the coming surge in launch rates. This could also apply to particles from thousands of constellations' satellites burning while reentering Earth's atmosphere, although the magnitude of their effects is yet unknown. A common assumption is that limitations to the human enterprise in space are of a purely technical and economic nature. This paper challenges this assumption, by highlighting the existence of environmental limits to the currently planned development of space activities. Risks arising from these limits are explored, and the importance of ecodesign in the space sector is emphasized. Finally, the paper discusses the future sustainability of proposed space projects in the context of global ecological transition.

Keywords: Environmental impact, Space sustainability, NewSpace,
Planetary boundaries, Limits to growth
PACS: 0000, 1111
2000 MSC: 0000, 1111

1. Introduction

The scale of anthropogenic actions on the Earth system has become so large that they are now the main driving force of environmental change, leading to the rise of a new geological era, the Anthropocene [1]. As a result, the stable environmental conditions that allowed human civilizations to rise and thrive are now under threat because of human activities. Undermining this stability could shift Earth subsystems into new states dangerous for humans. This means that there are biophysical limits that humans need to respect to keep Earth a “safe place”, as expressed by the planetary boundaries framework [2]. Our highly unsustainable contemporary societies are, therefore, facing the daunting challenge of rapidly transitioning towards a system operating within these limits while meeting fundamental human needs.

In this context, satellites provide key services to society including progress in space and Earth science, telecommunication, navigation, surveillance, and are particularly useful for environment and resource management. For instance, they provided major advances in climate science [3], monitor more than half of the 50 Essential Climate Variables, and are essential to inform decision-making for mitigation and adaptation [4]. This means that the sustainability of space activities is important and must be guaranteed.

However, the space sector is undergoing profound transformations, shifting from the “traditional space” driven by government investments to the “NewSpace”, primarily driven by commercial motivations: in 2019, commercial activities represented 79% of the global space economy [5]. This shift has been enabled by technological and business model innovations including advances in manufacturing, miniaturization, and reusable launch systems, leading to a significant reduction in cost and the appearance of new products and services [6]. As a result, the global space economy grew by 6.3% per year on average between 2009 and 2019, reaching a total value of 423.8bn\$ in 2019 [7], and is expected to reach 2.7tn\$ by 2045 [8]. Upcoming projects

include constellations consisting of thousands of satellites, reusable rockets, space tourism (suborbital flights, space flights, space hotels), but also more ambitious endeavors such as Moon bases, Mars colonization, rocket Earth-to-Earth transportation, asteroid mining, or space-based solar power (Fig.1).

Space activities are, therefore, on the verge of a great increase. But like all human activities, they have impacts on the environment. This paper reviews the most critical impacts of the space sector as well as their potential growth, analyzed together in a comprehensive approach for the first time. Pollution from objects in space (space debris and night sky pollution) is described and the use of a framework based on planetary boundaries is proposed as a way to express its limits. Then, atmospheric impacts and associated regulatory risks are detailed. Limits to the development of space activities emerging from these environmental impacts are outlined, and the relevance of their consideration by actors in the space sector is emphasized. Finally, the future of the environmental, economic, and social sustainability of the space sector in the context of global ecological transition is discussed.

2. Limits due to pollution on orbit

2.1. Space debris

Since the beginning of the space age with the launch of the first satellite Sputnik in 1957, there have been 6000 launches placing about 12000 satellites in orbit according to the ESA Space Environment Statistics [26]. Today, among the 29000 tracked objects in orbit, only 4600 (16%) of these objects are intact, operational satellites. The rest is made up of derelict spacecraft (payload or rocket parts) and fragmentation debris due to explosions, collisions, tiny flecks of paint, etc. Due to this variety, debris is usually classified by size in three categories [27]:

- large-sized debris ($>10\text{cm}$), generally possible to trace, with a population of 34000 objects.
- medium-sized debris (between 1cm and 10cm), sometimes possible to trace, with a population of 900000 objects.
- small-sized debris (between 1mm and 1cm), not traceable, with a population of 128 million objects.

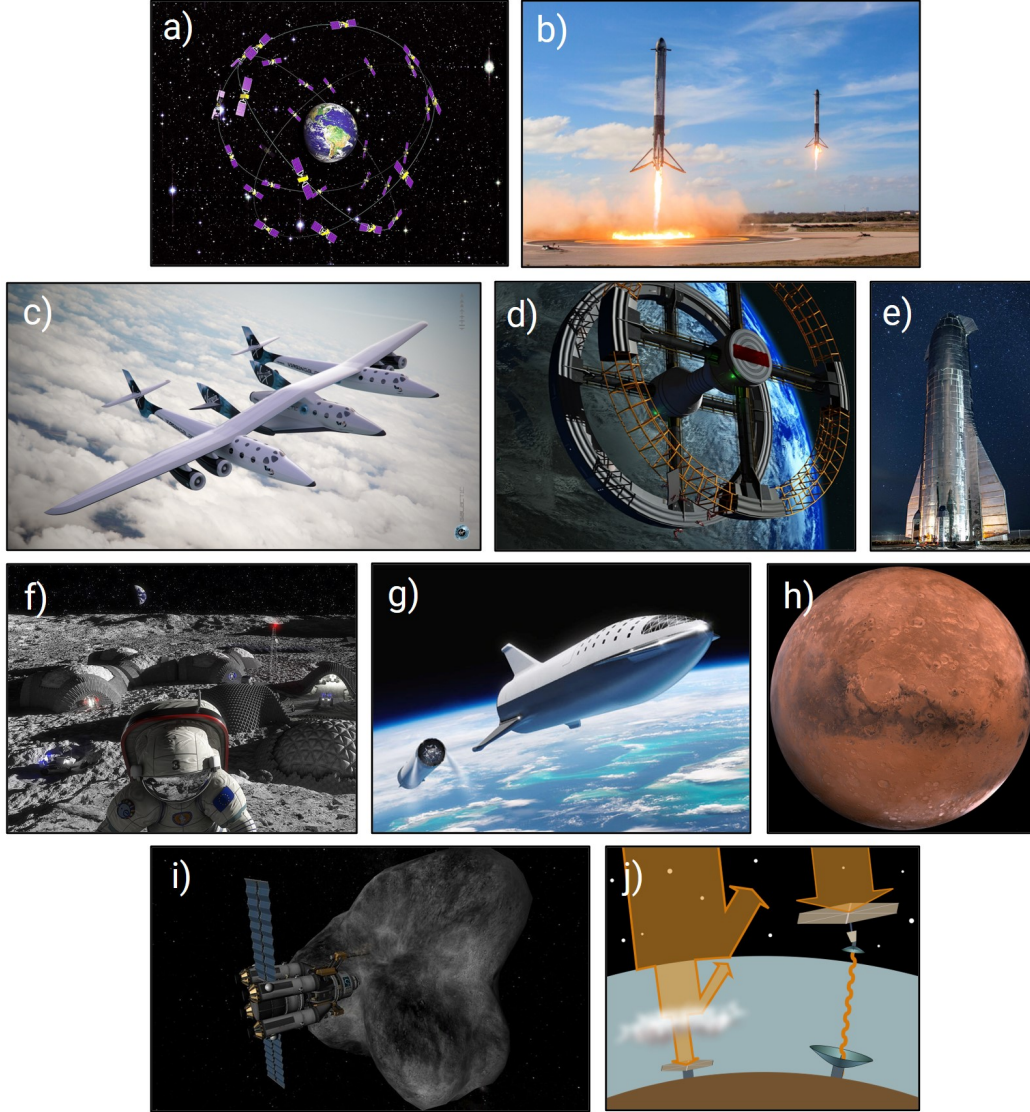


Figure 1: **Illustrations of current and future trends and projects.** a) Satellite constellation. Almost 100 companies are proposing one, with the majority to be launched in the 2020s [9, 10]; b) SpaceX's Falcon Heavy boosters landing in 2018 [11]; c) Virgin Galactic's SpaceShipTwo for space tourism and its carrier aircraft. First tourism trips in 2021 [12]; d) Several companies announced plans of space hotels for the coming years [13, 14]; e) SpaceX plans to develop Earth-to-Earth hypersonic travel using its Starship, connecting New York to Shanghai in 39mins. First tests possibly in 2022 [15, 16]; f) NASA plans to build a base on the Moon by the end of 2020s as part of its Artemis program [17, 18]; g) SpaceX's Starship en route to Mars. First crewed flight planned in 2026 [19]; h) SpaceX plans to send 1 million people to Mars by 2050 (>1000 flights/year required) [20, 21]; i) Asteroid mining. First sample return mission completed in 2020. First commercial mission \approx 2040s [22, 23]; j) Space-based solar power. China plans to generate 1MW by 2030, and to have a commercially viable plant by 2050 [24, 25].

Due to their high relative velocity ($\approx 15\text{km/s}$ [28]), a collision between a spacecraft and debris is likely to be catastrophic. A collision with large debris leads to a complete disintegration of the spacecraft, generating, in turn, thousands of additional debris. Medium-sized debris can either lead to complete disintegration or heavy damage, while small-sized debris cause minor damage that can eventually lead to mission failure. The number of objects in orbit has been steadily increasing, almost doubling over the last decade (Fig.2). There have been two major events contributing to this continuous increase. In 2007, a Chinese anti-satellite missile test on the satellite Fengyun-1C resulted in the largest debris cloud ever generated by a single event (+25% in debris population) [29, 30]. In 2009, a collision between Iridium-33 and a defunct Russian satellite, Cosmos-2251 generated 2296 catalogued debris and hundreds of thousands of untraceable debris, which became a threat for other satellites within the Iridium constellation potentially orbiting close to the debris cloud [31]. To avoid such catastrophic events, satellite operators perform collision avoidance maneuvers when passing near a traced debris. However, untraceable objects cannot be avoided by nature, meaning that they cause a permanent risk of potential mission failure [32].

In 1978, Kessler and Cour-Palais [33] theorized that the orbital debris population could reach a critical density above which cascading collisions between debris could self-sustain even without additional launches, eventually making the space environment unusable for hundreds to thousands of years. The concern on this “Kessler Syndrome” was later emphasized by many studies, including D.Kessler discussing “limits of population growth in LEO” [34] (Low Earth Orbit). Currently, the number of objects is expected to continue to increase, even without additional launches [35]. Most of the traffic in space is concentrated in the LEO region, at an altitude ranging between 200km and 2000km, with about 3300 functioning satellites along with the International Space Station. It is also the most crowded region in terms of debris, hosting 55% of the total catalogued population [35]. The loss of the LEO region due to debris would impact all the space economy, but more importantly, it would disable essential services upon which society relies such as GPS-based navigation, communications, early warning systems, and meteorological and environmental monitoring services.

Efforts have been made by the international community to mitigate space debris with guidelines developed by the United Nations Committee on the

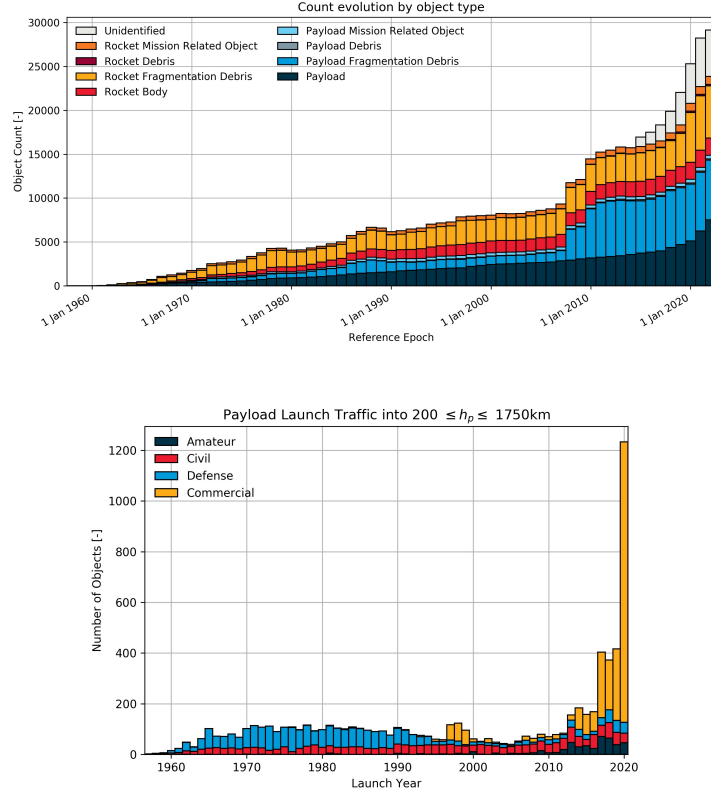


Figure 2: Evolution of the number of objects in orbit per object type (top). Evolution of the payload launch traffic in Low Earth Orbit per mission funding (bottom). [35]

Peaceful Uses of Outer Space (UNCOPUOS). The compliance rate to these guidelines has been increasing in the last 5 years [35]. In addition, the field of on-orbit servicing is emerging, aiming at expanding spacecraft lifetimes by repairing, refueling, or upgrading them in-situ, thereby delaying debris creation. Remediation measures are also being considered with several missions of debris removal planned in the coming years, but they only target defunct satellites to prevent them from generating additional debris [36]. Their remediating potential is, therefore, significantly limited and making these missions commercially viable will be challenging.

On top of this, recent plans of launching constellations of small satellites are raising growing concerns. In 2020, Curzi et al. outlined about one

hundred companies or agencies proposing satellite constellations [9]. In particular, some commercial companies (such as SpaceX, OneWeb, Amazon, or China Satellite Network Group) have announced plans to launch large constellations – mostly in LEO – representing over 20000 satellites by 2030, and possibly over 60000 in the following decade [37, 38, 39]. This is a tremendous increase with respect to the initial population in orbit of about 2000 operational satellites (in 2018) and the 8100 payloads launched since the beginning of the space age [32] before 2019. Most of these large constellations aim at enabling ubiquitous access to high-speed internet services, even in regions lacking the necessary infrastructure. Starting in 2019, SpaceX has already launched 1735 satellites of its Starlink constellation, while OneWeb has launched 146 (as of August 2021).

Several studies have investigated the effect of introducing these constellations on the space debris population. They found that collision rate increase is to be expected, showed that high reliability and strong compliance to space debris mitigation guidelines are absolutely necessary, and even argued that these guidelines and current models need to be updated to face this new threat [31, 32, 40, 41, 42].

2.2. Night sky pollution

In addition to endangering the sustainable use of the space environment, large constellations can, by reflecting sunlight back to Earth and emitting radio signals, negatively impact the visibility of the night sky and interfere with professional astronomical observations [43]. After the launch of the first satellites of SpaceX’s Starlink, many astronomers have reported satellite trails, sometimes visible to the naked eye, disturbing their work [44]. The International Astronomical Union (IAU) subsequently presented a report to UNCOPUOS making recommendations to keep “dark and quiet skies for science and society” [45]. They emphasized that the aggregate effects of constellations have not been properly investigated while reminding that astronomical discoveries can continue only if the night sky remains clear and unpolluted. Along with communication satellites, there have been other concerning propositions [46] such as artificial moons to light a Chinese city [47] or orbital billboards to advertise the night sky [48]. In 2018, the launch of an artistic “disco-ball” surprised the astronomical community and was even described by some as “space graffiti” [49]. The momentary attention created

by these sporadic events on this issue is likely to become persistent due to recent findings. Kocifaj et al. [50] found that artificial space objects including satellites and space debris were responsible for a new skyglow effect increasing the night sky brightness (NSB) already as much as 10% over natural levels. This is above the threshold set by the IAU to define an astronomical site as light polluted.

2.3. New boundaries

Breakups or collisions lead to an increased exposure to space debris for other satellites, thereby degrading the orbital resource [51]. Space debris is, therefore, a major threat to the long-term sustainability of space activities. As the debris population will likely increase even without additional launches, this means that the carrying capacity of the LEO “ecosystem”, defined as the maximum number of orbiting satellites that can be sustained in the long run, may have been overshoot (Fig.3). The pristine night sky is a common heritage of humankind: the discussed changes may have, in addition to impacts on stargazing and scientific inquiry, unforeseen effects on wildlife, human health, and cultural and religious practices. Without further precaution, the unregulated action of private interests in space could lead to the tragedy of two commons — the near-Earth orbital environment and the night sky — which must be avoided.

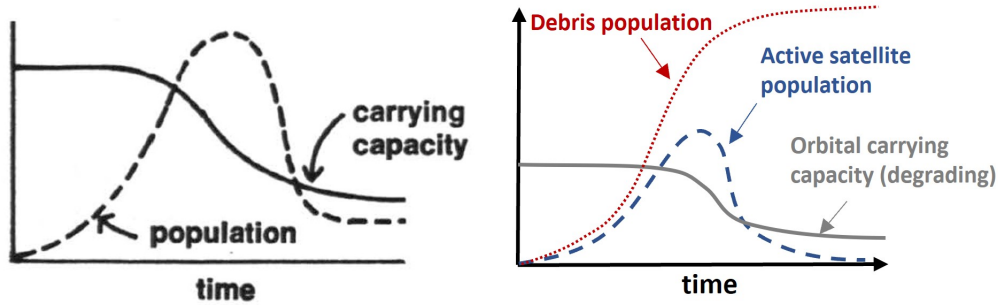


Figure 3: Left: in many natural ecosystems, uncontrolled growth leads the population to overshoot the carrying capacity and collapse, decreasing the carrying capacity in the process. Limits to Growth, 1972 [52]; Right: overshoot of the object population in orbit (debris+active satellites) leading to cascading collisions causing the collapse of the active satellite population and degradation of the orbital carrying capacity. The timescale of this process could be tens to hundreds of years. This can be avoided by removing objects from orbit and by not placing new ones into most critical regions.

In 2009, Rockström et al. proposed a framework based on planetary boundaries to define preconditions for human development. These boundaries are thresholds associated with Earth system processes that, if crossed, will trigger non-linear, abrupt environmental change [2]. The formulation of new boundaries for the proliferation of objects in orbit and night sky brightness (Tab.1) would make use of the widely adopted concept of planetary boundaries to encourage sustainable action and avoid or limit their transgression.

Although the proliferation of the number of objects in LEO is not an Earth system process, an orbital boundary mirroring planetary boundaries could be defined. A reasonable threshold associated with abrupt environmental change in terms of objects in orbit could be the object flux such that the rate of fragment production equals the rate of removal by atmospheric drag [33, 34, 53]. Crossing this threshold would result in the debris population increasing even without additional launches, meaning that, as defined, the orbital boundary has already been transgressed.

In addition, light pollution could fit well in the planetary boundaries framework. As the contribution of anthropogenic sources of light to the NSB is rapidly increasing due to space objects, the definition of a specific boundary could prove relevant to anticipate deleterious effects. The relevance of the following discussion goes beyond the space sector since many other anthropogenic activities contribute to night sky pollution. Existing literature on natural and artificial NSB makes the estimation of a pre-industrial and a present value already possible, as was done by Rockström et al. for the Earth system processes they selected. Although the natural NSB is varying widely, a level of $22.0 \text{ mag/arcsec}^2$ in the Johnson-Cousins V band has often been reported [50][54], corresponding to a visual luminance of $200 \mu\text{cd}/\text{m}^2$ [55][56]. Assuming that the light pollution at pre-industrial times was small, meaning that NSB was close to its natural value, this value could be considered to be the pre-industrial luminance of the night sky. To estimate the present value, global and land averages were approximated using the mapping of artificial NSB of Falchi et al. [57]. The scale was corrected because it is based on a reference value for the luminance of the night sky of $174 \mu\text{cd}/\text{m}^2$, while the previously cited studies revised this estimation to $200 \mu\text{cd}/\text{m}^2$. Present day, global average luminance of the night sky was found to be $256 \mu\text{cd}/\text{m}^2$. As very little light pollution is expected on sea, a land average was also

computed, yielding a much higher value of $390\mu\text{cd}/m^2$, almost twice the natural luminance. Then, although probably very challenging to evaluate, a boundary for the luminance of the night sky could be based on its proven deleterious effects on wildlife [58, 59, 60] and human health [61, 62]. The definition and calculation of this value are, however, well beyond the scope of this paper.

	Process	Parameters	Boundary	Current status	Pre-industrial value
Proposed by Rockström et al. (example)	Climate change	(i) Atmospheric CO ₂ concentration (ppm)	350	387	280
		(ii) Change in radiative forcing (W/m^2)	1	1.5	0
Proposed in this paper	Light pollution at night	Luminance of the night sky ($\mu\text{cd}/m^2$)	TBD*	256 (global) 390 (land)	200
Proposed in this paper	Proliferation of objects in orbit	Average object flux in LEO	TBD	TBD	Natural meteoroid flux

Table 1: A new planetary boundary for light pollution at night; An “orbital boundary” for the proliferation of objects in orbit. *To be determined.

3. Impacts on the Earth’s atmosphere: is the sky the limit?

3.1. The unique nature of rocket emissions

The amount of material emitted by the ≈ 100 rockets launched every year is about 40000 tons, only 0.01% of the fuel burned by the global aviation sector [63]. However, during their ascent from ground to orbit, they release gases and particles in all the layers of the atmosphere. This is a unique characteristic because rockets are the only anthropogenic source of pollution in the middle and upper atmosphere, that is, above 15 km where airlines emissions stop [63]. Emissions into the troposphere, the lower layer of the atmosphere, are not important besides transient, local pollution. However, emissions in the stratosphere, the layer above the troposphere, are more concerning for two main reasons. First, the stratosphere being dynamically isolated from the troposphere, emissions components of hundreds of launches accumulate for several years [64]. Then, the stratosphere is the home of the ozone layer, a region of high concentration of ozone at 15–35 km altitudes, absorbing most of the Sun’s harmful ultraviolet radiation and thereby protecting living organisms on the ground (Fig.4).

In addition to these particularities, the magnitude of the effects of rocket emissions on the atmosphere varies significantly depending on the type of propellant combination used. Liquid Rocket Engines (LREs) use propellants in the liquid form, such as liquid oxygen combined with liquid hydrogen as a fuel (e.g. Ariane 5) or kerosene (e.g. SpaceX’s Falcon 9). This allows thrust variability, but LREs are often coupled with Solid Rocket Motors (SRMs) (e.g. Ariane 5 boosters) because they grant higher energy density for lift-off. SRMs typically use a combination of solid aluminium fuel with ammonium perchlorate as an oxidizer. A third type of rocket is being used more recently: Hybrid Rocket Engines (HREs), using a liquid oxidizer and a solid fuel, often a hydrocarbon. They grant high safety, making them popular for space tourism applications (e.g. Virgin Galactic’s SpaceShipTwo). Although there are still many uncertainties and serious knowledge gaps on the effect of launch emissions on the atmosphere [64], estimates of orders of magnitude are available in the literature.

3.2. Stratospheric ozone depletion

During the lifecycle of complete space missions, the launch event has been reported to contribute to almost 100% of the ozone depletion potential [65]. Ozone is destructed mostly by highly reactive radicals (oxides of chlorine, nitrogen, bromine, and hydrogen), with a single molecule able to destroy up to 100000 ozone molecules [66]. Ozone depletion from SRMs particles has historically been the main concern with the first studies carried out by Cicerone in 1974 [67]. LREs exhausts contain less reactive chemicals and particles and are, therefore, responsible for ozone loss one order of magnitude smaller than SRMs [66]. The ozone loss caused by the global launch fleet has been estimated to be greater than 0.01% and less than 0.1%, with regional effects reaching several percent and with complete destruction in the surroundings of exhaust plumes [68]. This is to be compared to the ozone loss caused by ozone-depleting substances (ODSs) banned by the Montreal Protocol of about 3% [64] (of the total amount of ozone).

As a consequence, the present-day contribution of rockets to ozone loss is small. It represents a few percent of the total anthropogenic contribution to ozone depletion, about the same relative impact that global aviation has on climate radiative forcing [66]. However, the trends discussed in the introduction make an increase of launch emissions by a factor of 10 credible, which would make the contribution of rockets comparable to that of banned

ODSs, as Ross and Vedda warn [64]. A 2009 study highlighted the limitations to the growth of the space sector due to ozone depletion. It showed that, considering launch rates required by proposed space systems at that time (i.e. to be implemented in the future), global ozone loss could become significant, even using only LREs [66]. Moreover, a 2010 study found that a fleet of 1000 launches per year of hydrocarbon-based HREs typically used for space tourism would cause ozone loss up to 6% in polar regions [69]. With the anticipated growth of the space sector, the contribution of rockets to ozone depletion will inevitably increase in the future. As the study warns, there will be a growing risk of regulation of rocket exhaust compounds in the name of ozone protection. Important data uncertainties combined with the fact that the Montreal Protocol lacks adapted metrics to tackle rocket emissions effectively make this risk even more important [64]. If left unregulated, by 2050 rocket emissions could deplete ozone more than ODSs ever did [70].

3.3. Contribution to climate change

While the effect of rocket emissions on the ozone layer has been studied for several decades, the concern about their impact on climate is more recent. Available life cycle assessment studies of space missions are scarce and often do not account for emissions occurring during the launch event, or only partially, due to lack of data availability and modeling complexity [65, 71, 72, 73]. Yet, launch emissions are likely to be the most important contributor to the impact on climate change of the global space sector.

Rocket exhausts contain greenhouse gases (e.g. CO₂, H₂O) but also particles (e.g. alumina, black carbon). The amount of greenhouse gases emitted by rockets is dwarfed by that of other industrial sectors, making their contribution to the problem insignificant. However, the effect of particles is much more concerning. Black carbon particles accumulate in the stratosphere and absorb a fraction of sunlight, resulting in a warming of the stratosphere. Because some rockets can emit about 10000 times more black carbon than modern turbine engines [63], the amount of black carbon emitted by rockets in the stratosphere in 2018 was comparable to that emitted by global aviation [74]. On the other hand, alumina features a more complex behavior by both reflecting incoming radiation into space and absorbing upwelling radiation from the Earth. This also results in a warming of the stratosphere [63]. At the same time, the reduction in solar flux caused by this accumulation of

particles in the stratosphere leads to a cooling of the lower atmosphere (the troposphere) and the ground (Fig.4).

In 2014, Ross and Sheaffer estimated that rocket emissions globally contributed to cool the troposphere by about $16 \pm 8 \text{ mW/m}^2$, with relative contributions of 70% for black carbon, 28% for alumina, 2% for H_2O , and $\approx 0\%$ for CO_2 [63]. This means that hydrocarbon-based rockets emitting black carbon (e.g. kerosene-fueled LREs, or most HREs) and SRMs emitting alumina are responsible for most of rockets' climate impact. As a consequence, studies considering only CO_2 emissions to assess the contribution of rockets to climate change underestimate it by several orders of magnitude. Although this value is only an approximation subjected to uncertainties and requiring further confirmation, the study makes an interesting comparison with the contribution of global aviation to radiative forcing, which in 2014 was bigger only by a factor of 4, in absolute values [63]. This means that the magnitude of cooling of the troposphere from rockets is comparable to the magnitude of warming from aviation.

However, this should not be interpreted too quickly as something “positive”. Stratospheric injection of particles has long been discussed by climate scientists as a method of solar geoengineering to counteract the warming of greenhouse gases. But this has always been very controversial and encountered strong opposition. Rocket emissions compounds act as geoengineering agents and, therefore, launchers are already beginning this process in an uncontrolled manner, while black carbon geoengineering — on a much larger scale — has been found to present potentially catastrophic side effects [75]. In addition, since rocket emissions are not distributed homogeneously around the globe, they can cool the troposphere in certain regions but still warm it in other regions because of the complex response of the global climate [69]. Consequently, Ross and Vedda warn that it is uncertain how policymakers would respond to significant growth in launch activities in a context of growing concerns on climate intervention. Once again, this risk is further increased by the lack of confidence in current radiative forcing estimations [64].

The projects mentioned in the introduction could fuel such an important growth. For instance, after a decade of launches at a rate of 1000 per year, the fleet of hydrocarbon-based HREs (typical for space tourism applications)

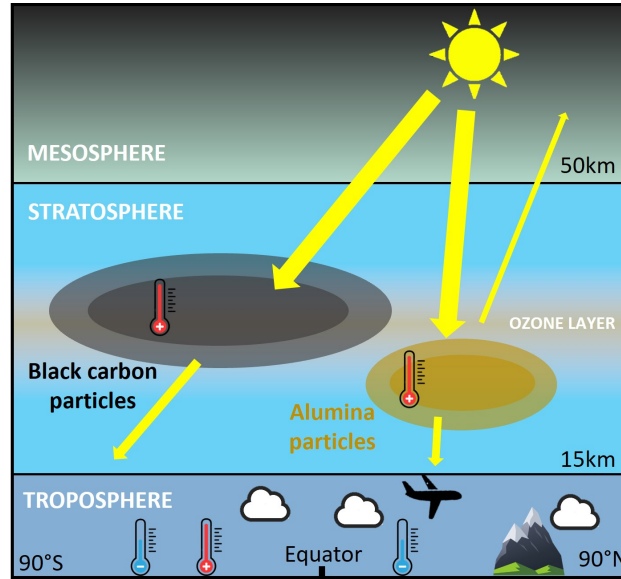


Figure 4: Effects of rocket particle accumulation in Earth’s atmosphere: stratospheric injection of particles destroys ozone, but also warms the stratosphere, resulting in a global cooling of the troposphere and circulation changes that can result in regional warming (locations in the figure are purely indicative). Inspired from: The Policy and Science of Rocket Emissions, The Aerospace Corporation [64].

would create the same radiative forcing as global aviation [69], and could rise polar surface temperatures as much as 1°C . Interestingly, Ross and Sheaffer estimated that the carbon footprint of a passenger in a typical sub-orbital space tourism flight is comparable to that of a passenger travelling thousands of times in aircraft between Los Angeles and London [63]. This illustrates that, in addition to possible future policy implications, the potential climate impact of space tourism raises important issues related to climate justice in the age of “flygskam”. But space tourism is not the only emerging market with high launch rate potential. The Chinese solar power plant is planned to require more than 100 launches of Long March 9, a heavy rocket fueled by kerosene [24]. Current plans of SpaceX for Earth-to-Earth travel and Mars colonization will be based on its Starship that relies on a liquid oxygen/liquid methane combination expected to be less harmful than kerosene, but this may be largely offset by the significant associated increase in launch rate.

3.4. Impacts of reentry

Due to natural orbital decay, objects in LEO ultimately fall back down to Earth and burn up when reentering the atmosphere. A common practice in the context of space debris mitigation is to voluntarily deorbit spacecraft by making them reenter Earth's atmosphere when they reach their end-of-life to reduce the population in orbit. However, particles originating from these burning spacecraft (e.g. aluminium) could have detrimental effects on the ozone layer or on climate. Particles of several metals resulting from thousands of large constellations' satellites reentering would exceed by far injection of natural origin such as meteorites, but the resulting effect is yet unknown [76]. Although purely hypothetical at this stage, it is possible that at a critical rate of reentering objects, the resulting pollution on the atmosphere reaches a level raising regulatory attention from policymakers. This could limit the rate of object disposal in LEO, thereby limiting the rate at which new objects could be launched there because the orbital resource is limited by the risk of space debris (Fig.5).

4. Environmental sustainability and beyond

4.1. Consideration of environmental limits

It is generally assumed that the only limitations to the development of the space sector are either technological or economic. However, the previous discussion shows that there are also environmental limitations that can arise either from (Fig.5):

- Transgression of the boundary of the proliferation of objects in orbit and/or associated regulations
- Transgression of the boundary of light pollution at night and/or associated regulations
- Regulations on climate radiative forcing and ozone depletion from launchers emissions
- Regulations on climate radiative forcing and ozone depletion from spacecraft reentry emissions

These limits are intertwined. A satellite disintegrated into debris is likely to have a higher contribution to NSB than its intact version because of increased reflecting surface area, implying that space debris proliferation could

aggravate night sky pollution. In addition, a recent study found that ozone destruction leads to a degradation in plants' capabilities to store carbon because of damages from UV radiation [77]. Impacts of rockets on ozone, therefore, indirectly increase their contribution to climate change. In these cases, this also means that measures to mitigate environmental impacts can have co-benefits. On the contrary, as previously discussed, space debris and the atmospheric impacts of reentry have conflicting mitigation measures.

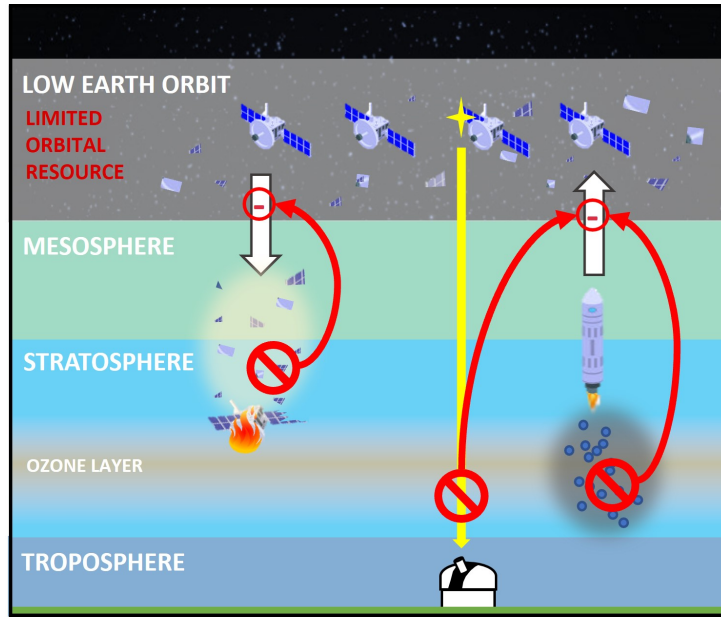


Figure 5: The number of operational satellites in LEO is limited by space debris, and could be limited by regulations on night sky pollution. Regulations on launch emissions and satellite reentry particulates in the name of ozone protection or climate intervention would limit object launch rate and disposal rate, respectively. This constitutes fundamental constraints to the space sector's growth.

4.2. Sustainability assessments and ecodesign of space systems

The consideration of environmental issues in the space sector is very recent, but there is a growing interest in assessing and mitigating the impacts of space activities. The European Space Agency is leading the development of Life Cycle Assessment (LCA) and ecodesign practices with its Clean Space initiative started in 2012. LCA in space applications presents various specific challenges, such as the difficulty of data collection and the need for specific

data sets due to the use of specialty materials, advanced manufacturing processes, and small production volumes [73, 78]. In addition, space activities can pollute in unique, sector-specific ways requiring extensions of the LCA scope. A framework for assessing impacts on space debris within LCA was recently developed [51] and applied on an existing mission [79]. Some authors have even considered extensions of the LCA scope for space exploration and space travel [80]. While this is an interesting exercise, more pressing, new concerns on night sky pollution could make the inclusion of this parameter also relevant, especially for large constellations.

A first attempt to assess the sustainability of the global space sector was carried out by A. Wilson in his PhD thesis [81], using a streamlined Life Cycle Sustainability Assessment evaluating environmental, social, and economic impacts. The approach consists of an approximation of these impacts over one year, which are compared to 2010 worldwide impacts and planetary boundaries. In a future scenario assuming 750 launches per year delivering 5000 spacecraft into orbit, the contribution of the space sector to climate change was found to reach 1.77% of the associated planetary boundary, and 1.54% for ozone depletion. These results are already significant considering the small relative size of the space sector with respect to all human activities. Moreover, it is important to note that despite being a major source of concern, the effects of black carbon and alumina on climate change and ozone depletion were not characterized due to knowledge gaps. Instead, black carbon was not considered in rockets' exhaust compositions and alumina was reported as a flow indicator. In addition, the impacts of other emissions were calculated using characterization factors that were not altitude dependent, again due to knowledge gaps, meaning that emissions in the troposphere and in the stratosphere had the same effects. It is therefore urgent to bridge these gaps to enable sustainability assessments accounting for these most critical impacts. This is a necessary condition to be able to make recommendations to the industry on how to design cleaner launch systems.

Ecodesign practices are particularly relevant for the space sector which is characterized by stringent safety and reliability requirements and very long lifecycles from design to exploitation phases. Decisions that can be critical for the environmental performance of a space system are made in the early development phase [82] and later changes are often impossible after the qualification of the design. Development cycles of launchers usually vary

between 5 and 10 years, while the exploitation time is as long as possible to recover development costs. For instance, Ariane 5 made its maiden flight in 1996 and is still flying today. This means that launchers that are currently under development may still be operating in 2050.

This causes several risks for the space sector. In the context of the European REACH regulations (Registration, Evaluation and Authorisation of Chemicals), obsolescence risks were identified for the space industry [83], which would undermine the quality, reliability, or even the feasibility of a technology. Regulatory obsolescence can arise from a legal ban on chemical substances, while commercial obsolescence can occur when suppliers change a product used by the space industry because larger sectors stop using it. It was reported that 20% of the materials used in the space industry may be affected in the long term [83]. These risks related to REACH are insightful for those that can be caused by the environmental limits previously outlined: for instance, a regulation on stratospheric injection of black carbon could make a launch system obsolete way before its planned date of end of exploitation, resulting in significant losses for the operator.

4.3. Space activities in times of environmental breakdown

Fast and continuous growth of space activities over the next decades, fueled by the various projects described in the introduction, could pose serious threats to both the space and Earth environments. However, in the same period, the global economy, energy systems, and social structures will undergo profound transformations due to the global environmental threats of climate change, biodiversity loss, freshwater scarcity, resource depletion and various forms of pollution. Responding effectively to these challenges will very likely constrain economic growth, given that the green growth paradigm — the decoupling of economic growth from environmental pressures — lacks empirical evidence, is highly unlikely to be achieved rapidly enough to meet climate targets and is unlikely to happen at all [84, 85, 86]. This will also create tensions on some resources, as many studies have reported a dramatic increase in material requirements for a transition to a low-carbon society [87, 88, 89, 90, 91, 92, 93], with some materials having high levels of criticality [94, 95].

In this context, in addition to their potentially severe impacts on the environment, the significant economic, energetic, and material requirements

of some proposed space projects like space colonization and Earth-to-Earth transportation could be prohibitive. They could also become increasingly socially unacceptable and ethically questionable. Furthermore, proposed space-based solutions to overcome these energetic and material issues on Earth (e.g. large-scale space-based solar power and asteroid mining) are not relevant in the timescale of the transition to meet climate targets. For instance, the pioneer Chinese space-based solar power plant is planned to reach 1GW by 2050, which over a year would produce only 0.1% of its 2018 electricity needs, expected to grow by 2050 [96]. This will be a meager contribution to China’s carbon neutrality planned for 2060, not to mention the plan to phase out coal by 2040 as required for 1.5°C compatible pathways [97]. On the other hand, as the mineral requirements for clean energy technologies would increase by a factor of 6 by 2040 to reach global carbon neutrality by 2050 [88], space mining is not credible as a potential solution in this context. As a result, the space industry, which relies on high social, industrial, and technological complexity, international supply chains, and critical materials [98], may see its predicted growth, planned agenda, and established politico-economic support seriously challenged in the next decades. Given the long design and lifecycle timescales of space projects, the space sector’s decision-makers should also consider these constraints when making plans for the future, in addition to the environmental limitations previously outlined.

Considering the environmental limits to the space sector’s growth discussed, the trends of fast growth, commercialization, and search for maximization of profit that are fueling the NewSpace must not undermine space activities that are unambiguously beneficial for mankind. In addition, beyond considerations on the applications of space technologies, the existence of environmental limits constraining the development of space activities has important implications for the future expansion of mankind in space. The visions of space as a new frontier that mankind will inevitably conquer and of a future in which humanity becomes a multi-planetary species are challenged by the physical reality of planetary and orbital boundaries: we may find that shooting for the stars comes at an unbearable cost for the Earth’s environment.

5. Conclusion

This paper reviews the environmental impacts of the space sector as well as their potential future evolution based on proposed plans, and highlights the existence of environmental limits to the development of space activities, for the first time to the author’s knowledge.

The space debris situation is identified as critical since, in some orbital regions, the object flux is already so high that the total number of objects in orbit is expected to increase even without additional launches. As the number of satellites in orbit will soar in the coming years with the launch of large constellations, the situation is likely to deteriorate significantly. In this context, the ability of proposed mitigation and remediation measures to reduce the degradation of the orbital environment to sustainable levels — a “green growth” of operational objects in orbit — still remains to be proven. Regarding night sky pollution, recent findings showing that the contribution of space objects is already important combined with plans of large constellations are likely to increase the already growing concerns of the astronomical community and the general public, and result in unknown impacts on natural and human life. The risk of multiple tragedies of the commons from the proliferation of objects in orbit and night sky pollution was emphasized. Then, the definition of an orbital boundary related to the proliferation of the number of objects in orbit mirroring planetary boundaries was proposed, while the inclusion of light pollution as a new planetary boundary was suggested, with a reported pre-industrial level of $200\mu\text{cd}/\text{m}^2$ and an estimated present level of $256\mu\text{cd}/\text{m}^2$ ($390\mu\text{cd}/\text{m}^2$ on land).

The impacts of the space sector on stratospheric ozone depletion and climate change are likely to be dominated by emissions of launch events. While present-day contributions of space activities to ozone depletion and climate change are small compared to other industrial sectors, proposed plans could lead to much higher levels raising regulatory attention from policy-makers. Most concerning rockets are SRMs and hydrocarbon-based HREs and LREs. However, the review showed that even cleaner propellants could create important impacts considering the coming increase in launch rates. In addition, this study highlighted the important knowledge gaps preventing current LCA studies to properly characterize the impacts of the launch event, as well as spacecraft reentry.

Putting in perspective these environmental impacts with current trends in the development of space activities, this study outlined several environmental constraints constituting fundamental limits to the space sector's growth. The risks arising from the existence of these limitations for actors of the industry were discussed, and the relevance of the implementation of ecodesign practices was emphasized.

Additionally, the relevance and sustainability of some proposed space projects in the context of global ecological transition were analyzed and questioned. Projects featuring large energy and material requirements such as colonization or Earth-to-Earth transportation are likely to meet difficulties and encounter growing opposition from the general public as the global environmental crisis unfolds.

Finally, this paper paves the way for future work on several aspects. In particular, it calls for addressing the important knowledge gaps on the environmental impacts of space activities. Then, the full definitions of proposed boundaries for the proliferation of the number of objects in orbit and light pollution at night remain to be done. In addition, the last subsection opens a discussion on the future of space activities in the context of global ecological transition, raising many questions that, from the author's perspective, need to be addressed. Lastly, because of the various issues raised in this paper, a quantitative assessment of the future evolution of the environmental impacts of space activities based on proposed plans is required.

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