Position Paper

Artificial space debris and Kessler syndrome.

A limitation for humankind.

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Abstract. *Space debris is an unuseful material moving in space. This debris can be both natural and artificial. This paper focuses on the currently increasing quantities of artificial debris and the ensuing series of problems. The main aim is to highlight the importance of one of these issues – the Kessler Syndrome – from a philosophical perspective. The Kessler Syndrome presents a situation in which, without a reduction of artificial debris in space and especially on Earth's orbit, humans will see their possibilities to keep exploring the universe reduced. If this Kessler Syndrome becomes a reality, human knowledge will be predictably self-limited due to the current lack of responsibility. As well as examining this theoretical hypothesis, this paper considers ways of promoting a sustainable future for space exploration, and thereby human knowledge.*

1. Introduction

Space debris is an unuseful material moving in space and can be both natural and artificial. This paper will focus on the currently increasing quantities of artificial debris. This debris implies a series of problems. The main aim of the text is to highlight the importance of one of these issues from a philosophical perspective, as well as that of the sociology of expectations. The specific issue referred to is the Kessler Syndrome. The Kessler Syndrome presents a situation in which, without a reduction of artificial debris in space, and especially on Earth's orbit, humans will see their possibilities to keep exploring the universe reduced. The lack of clear agreements on who is responsible for managing this debris maximizes the relevance of the situation.

The main hypothesis is that, if this Kessler Syndrome becomes a reality, it will imply a consequent reduction of human's ability to build new knowledge of the cosmos, and this limitation will be due to the current lack of responsibility. By applying the path initiated by the sociology of expectations, we can imagine the future shape of its development as a consequence of its performative power (Van Lente, 2012, 2021). Therefore, this paper intends to present the importance of establishing expectations which are coherent with sustainability when exploring the space.

Understanding society as a large group of people who live together in an organized way, making decisions about how to do things and sharing the work that needs to be done, requires establishing a set of principles and criteria that promote sustainability. That is, paraphrasing Brundtland (1987), exploring space in a way that meets the knowledge needs of the present generation without compromising the ability of future generations to meet their knowledge needs.

The structure of the paper is based on three points. In the first step, we examine what artificial space debris is, and what its current status is. Secondly, we consider arguments to show that this context involves a limitation for the sustainability of human's knowledge. Finally, we look at the main, as yet unsuccessful, attempts to solve this issue that have taken place thus far. This third point will be dealt with in the context of keeping on reflecting and researching about this issue and ensuring that it is not abandoned.

Through a deductive *methodology* we develop a theoretical hypothesis in a coherent and plausible way. As a consequence, the results will be of a conceptual nature, and not experimentally or empirically proven.

One of the limitations of the paper is that the premises involving space data used to reach the conclusion are based on official and public data. Nevertheless, due to the nature of the topic, this means recognizing that the latest data reflect the economic or geopolitical conflict of interests among the different agents involved. As a consequence, some data might not be fully updated or accurate.

This limitation connects to the nature of our methodology. This article is based on documentary research and any sort of field research or experimental research regarding artificial space debris that has been done by agents and institutions with higher resources and knowledge of the different necessary tools.

As a consequence, the premises used to demonstrate the hypothesis presented as true, false, or null are based on the testimony of experts in the area and their authoritative explanations. The assumption is that they collected and reflected reality accurately through scientifically based statements (for example, based on mathematic calculations), their direct evidence (for example, the astronauts), and their direct evidence through the devices used to collect the data (for example, from aerospace observatories).

2. Artificial space debris. Definition and current status.

2.1 What it is

Debris can be defined as "broken or torn pieces of something larger" (Cambridge Dictionary, n.d.). Talking about space debris, we can refer to natural debris or artificial debris. Natural debris is that one generated by, for example, parts of comets or asteroids. On the other hand, artificial debris is the one with a human origin (Johnson & McKnight, 1987).

Artificial space debris concerns pieces from spacecraft which are still in space and did not burn up in the atmosphere or land again on Earth. As a consequence, one part of this debris stays in space, particularly on Earth's orbit (Wild, 2021).

The material of this debris is differentiated, depending on its origin as well as its size. The size of this artificial space debris ranges from less than one millimetre to more than ten centimetres in diameter.

2.2 Where we are

Humans have shown interest in launching objects into space since the moment in which they acquired the skill of walking on two feet and using their eyes to look in front of them and up to the sky. Nevertheless, the nineteen forties were the origin of what we understand nowadays as space exploration, since the first rocket was launched beyond the stratosphere in that period (Bright & Sarosh, 2019). Since that moment, being present in space has had significant relevance: economically, military, ideologically, and logistically. As a consequence, more and more artificial objects have been launched into space with different purposes (Cadbury, 2006; Hardesty & Eisman, 2007). According to data provided by the European Space Agency (2022), 6180 rockets have been launched in the world since 1957.

This has led to in an increase of artificial space debris and the beginning of accidents caused by artificial objects in orbit. The first accident took place in 2009, generating more than 2300 fragments of new debris (ESA, n.d.). As a consequence, although it is true that much artificial space debris falls back to the Earth (approximately once a day), a significant amount of those objects remains in space (Wild, 2021).

This increase in the artificial objects in space has taken place due to the combination of different factors. One of them concerns the technical improvements that have taken place over the years, which has led to better capacities at a reduced price when talking about space exploration (Coopersmith, 2012; Harrison et al., 2017). This has allowed a higher number of national initiatives to be present in space in the form of Space Agencies, although not all of them have launch capabilities (ESPI, 2019).

The second factor is the emergence of new private agents in this activity. Indeed, the motivations and agents driving space exploration have extended well beyond traditional scientific objectives. Space tourism, with the intent of enabling individuals to experience the environment of space first-hand, is one example. Through ventures like Virgin Galactic, Blue Origin, SpaceX, or Sierra Space, companies aim to make space travel accessible to at least some civilians, thereby opening up a new realm of human experience and pushing the boundaries of adventure (Chang, 2015; Webber, 2013).

Furthermore, the expansion of space-based communications infrastructure has become a pivotal motivation. In an increasingly interconnected world, satellites and space-based networks facilitate global communication, data transmission, and the navigation systems that underpin modern society. Companies like SpaceX have embarked on ambitious projects to deploy massive satellite constellations, such as Starlink, with the goal of providing widespread high-speed internet coverage to remote and underserved regions around the globe. Another private agent who has shown interest in this is Amazon, with its Project Kuiper (Harris, 2019).

Moreover, there are private companies that provide services and technologies related to space exploration that can be utilized by military organizations. These private agents provide tools such as satellites for reconnaissance, surveillance, and communication that enhance a nation's ability to gather intelligence. Although the information regarding specific companies' involvement with military space exploration can sometimes be limited due to security and confidentiality concerns, the existence of companies such as Lockheed Martin or Northrop Grumman is well known (Hughes-Wilson, 2016, pp. 180–198).

In addition, the exploration of space is nowadays used for many other purposes, including advertisement, or meteorological services, such as Red Bull Stratos, and The Weather Company from IBM.

As a result of this synergy between public and private agents with multifaceted motivations, an expanding array of players, from established industry giants to innovative start-ups and small investors, continue to contribute to the dynamic and evolving landscape of space exploration (Hotz, 2012; Space Capital, 2022).

This new context statistically increases the chances of new accidents and the consequent increase of artificial space debris has not as yet led to significant solutions. And it is precisely because of this that the Kessler Syndrome exists.

2.3 The Kessler syndrome

According to space agencies such as the NASA and the ESA, in the middle and long-term the amount of artificial space debris will increase, as well as the accidents caused because of it. In fact, according to the ESA, "it is however expected that in the future collisions will become the dominant source of space debris" (ESA, n.d.; Space.com, 2015).

This context, in which the impact between different kinds of debris is the main source of new debris, implies a series of issues. One of them is constituted by the fact that some of this debris falls down into the Earth. Indeed, the quantity of debris returning to the Earth is estimated to be one piece a day, falling mainly into water since that is the nature of the majority of Earth's surface (Wild, 2021). This issue involves two risks. The first is the impact of this space debris and the damage caused when it does not fall into the water. Although legally, if a piece of debris falls onto your property you must receive compensation, according to the 1967 Outer Space Treaty or the 1972 Liability Convention, there are many situations that are not contemplated (Aganaba, 2021). Even when falling into seas or oceans, contamination is another big risk for the planet and its inhabitants. Nevertheless, this does not only involve the space debris fallen there. The South Pacific Ocean Uninhabited Area is informally known as the spacecraft cemetery. It is the part of the ocean where, regularly, space debris and other space instruments which are not useful anymore are thrown. This action is exacerbated by the lack of national legal duties (De Lucia & Iavicoli, 2019). As a consequence, space debris can originate security and contamination issues when on Earth.

The second issue is the fact that the average speed of debris impact in orbit, is 36001 km/hour (Wild, 2021). Any sort of crash at that speed is highly damaging and potentially lethal. Although Space Agencies have developed and keep researching ways to travel in outer space in a safer way, scientific research and its applications are by no means as fast as the speed of the debris creation. (Garcia, 2021)

As a consequence, we are in a context in which:

1. Space Agencies and private parties are sending more objects to outer space than ever.

2. Those objects generate debris, which can return to the Earth or stay in orbit.
3. When on Earth, that debris involves security and contamination issues.
4. When in orbit, the orbit already has natural debris, which is being naturally increased.
5. At this speed, artificial space debris impacts will be the main source of new artificial space debris.
6. At this speed, and with the current resources, artificial space debris is highly damaging and/or lethal in case of impact.

Thus, it follows that, if there are no changes in points 1 to 6, space exploration will become increasingly damaging and/or lethal.

Although the term Kessler Syndrome has never had a univocal definition, its origin can be tracked from 1978, when Kessler and Cour-Palais (1978) published an article in which they warned about this situation and predicted that random collisions between space debris would generate more random collisions, generating new debris, and so on.

This broke with the idea that space debris was not significant or big enough to be considered harmful. At the same time, they concluded that the way to avoid this escalation of events would be to reduce the non-operational artificial objects in orbit.

On one hand, this conclusion could seem to pose a false dilemma, since it is a future projection and does not take into consideration further discoveries and solutions. However, other studies conclude that this seems to be a real and not a false dilemma (Finkleman, 2014).

Nonetheless, the original article was key to putting this issue on the agenda. In fact, the term Kessler Syndrome became increasingly well known when the issue was taken up by popular magazines. Kessler extended his research and published a new contribution in 1981 (Kessler, 1981), while the most widespread publication of this issue for the general public, took place in 1982 (Schefter, 1982). The topic is still being developed and researched by different authors (Krisko, 2007; Madi & Sokolova, 2020).

3. A limitation for humankind

For the purposes of this paper, humans are considered to be rational entities. This does not mean that they are always rational, nor that their rationality does not know boundaries (Chater & Oaksford, 2010; Jonathon & Over, 1996; Mele & Rawling, 2004; Simon, 1990). At times, cognitive biases, or individual will, can change that (Chater & Oaksford, 2010). Moreover, sometimes humans actively create, write, and enjoy fiction. Nevertheless, humans have the skill of thinking rationally.

Someone who attends to, for example, a film about science fiction, rationally knows that the story is not real. Nor does its director pretend to present that story as true. The background is a rational understanding of the world. This understanding is mixed with creativity, unrealistic ideas, and a sense of excitement, but humans understand rationally the context. When this is not so, then there is an issue (BBC, 2021; Pearson, 2012).

When thinking about human passions, creativity, unrealistic or unprovable ideas, rational understanding also plays a key role. To be able to distinguish between what is true and what it is not, and to agree on what is real knowledge against what it is a belief or an opinion, we need evidence (Lanz, 1932; Stevenson, 2003).

According to Arp, Barbone and Bruce (2019), this evidence can come from seven different sources:

1. Direct evidence using our empirical skills.
2. Indirect empirical evidence through a device or tool which is reliably calibrated.
3. The testimony of others in whom we trust.
4. The testimony of experts in that specific area.
5. Authoritative explanations.
6. Logical or mathematic entailment.
7. Logically sound or cogent arguments.

Although our direct evidence using our empirical skills can sometimes be inaccurate, we all are familiar with this type of evidence. We use it every day. When we wake up and we hear the coffee machine, we conclude that the coffee is ready. When we see it is raining, we decide to take an umbrella. The same thing happens when humankind is trying to obtain evidence regarding how space is.

Different cultures have different words to refer to humans sent into space to obtain information about it. In English the most common terms are astronaut and cosmonaut. The origin of the word astronaut comes from *astron* + *nautes*, meaning "star + navigators". The term cosmonaut comes from *cosmos* + nautes meaning "universe + navigators". Independently of the language used to refer to them and the eventual differences of perspective they convey, humans have been sending other humans into space since April 12, 1961, when Yuri Gagarin travelled around the Earth in the spacecraft Vostok 1 (Kohli, 2017). On April 8, 2022, the private spacecraft Axiom Mission 1, crewed by Michael López-Alegría, Larry Connor, Mark Pathy, and Eytan Stibbe, was launch number 605 for human space travel (Margetta, 2022).

Although it is true that our empirical senses have some limitations, and it is not a trustworthy method of evidence in absolute terms, generally it is a source considered to be so, unless the contrary is proven (Hume, 1817; Russell, 1935). That is why still today we keep sending humans into the space, in order to obtain knowledge, and deliver it to future generations.

However, and if there are no significant changes in the context previously described, it will become too dangerous to send humans into outer space, or even impossible. This will involve the impossibility of obtaining evidence through these direct empirical senses. Thus, we can posit that:

1. If there are no changes, human direct exploration could become more dangerous and/or lethal than ever.
2. That danger could render direct human exploration no longer viable.
3. Direct empirical senses are a source of evidence.
4. Evidence is necessary for knowledge.

If there are no changes, it follows that human knowledge would be predictably self-limited due to the current lack of responsibility, although there are other sources of evidence.

Another way to obtain evidence is through a device or tool which is reliably calibrated. Although this kind of empirical evidence is mediated, it can be of high value. Space Agencies have been launching robots that, employing their sensors, cameras, and technological tools, can provide mediated empirical experiences. These robots can have different shapes and specific functions, and two of the most popular are Curiosity or Perseverance.

According to NASA, the calculated costs of sending a robot into space are lower than sending a human into space. NASA calculates these reduced costs taking in consideration that the robot does not need to sleep, eat, or go to the bathroom. At the same time, they can, generally speaking, last in space a longer time than a human. No less important, robots can do research in some conditions that humans could not. There is also a further factor which NASA considers when doing the calculations and must be reconsidered. According to NASA, "Sending a robot to space is also much cheaper than sending a human. [...] They can survive in space for many years and can be left out there—no need for a return trip!" (NASA Space Place, 2021).

Independently of future factors, such as if the costs will be reduced, or if it will become mandatory to make those robots return, the cost of producing them and keeping them in space are very significant. For example, Curiosity's and Perseverance's cost was about 2,9 and 3,2 billion US Dollars each, adjusted to 2021's inflation (McCarthy, 2021; NASA, 2012, p. 6).

These costs are too high to be spent regularly. They can be spent, but not without having some statistical security that those robots will be able to provide us the expected indirect evidence through their systems and tools. As a consequence, if the situation does not change, it will predictability be too expensive or even impossible to keep sending artificial tools to get indirect evidence to expand our knowledge regarding the space. Thus, we can posit that:

1. If there are no changes, human indirect evidence through well-calibrated devices could become more highly dangerous and/or expensive than ever.
2. That risk and its related costs could make human indirect exploration not viable.
3. Indirect evidence through well-calibrated devices and tools are a source of evidence.
4. Evidence is necessary for knowledge.

If there are no changes, it follows that human knowledge would be predictably self-limited due to the current lack of responsibility, although there are other sources of evidence.

Although it is true that, on many occasions, we base our knowledge on the people we trust, in the case of space exploration, this has to be relativized. The reason is that not everybody who we trust are experts in all the domains. I can trust my father to provide me some information regarding my childhood, but I would not trust him if he is trying to explain to me how to decipher the DNA of the biggest jelly fish from the ocean. The reason for that is simply that although he has all my trust as a person, he does not have enough specific knowledge regarding DNA, or jelly fishes, or the ocean's wildlife to be considered an expert. In consequence, his statements regarding this topic must not be considered evidence. Precisely, this confusion, called Inappropriate Appeal to Authority, is one of the main origins of misinformation (O'Connor & Weatherall, 2019; Vraga & Bode, 2020).

At this point, it is important to highlight that an expert only has authority if he can be proven wrong through falsifiability. Trusting someone as an expert, without falsifiability, is dogmatism (Popper, 2002). When talking about space, like in any other scientific field, experts can as well fall into the trap of misinformation (West & Bergstrom, 2021). Nevertheless, every source of legitimate expertise comes solely from authoritative explanations which are sound or cogent, and based on solid evidence. Because of this, it is possible to identify the scientists and channels that are not promoting knowledge through authoritative methods and evidence. After their identification, this category in the specific field or topic is removed by the scientific community. (Gunaydin & Doğan, 2015; Hopf et al., 2019; Obradovic & Barcus, 2020)

Due to this fact, when we have knowledge regarding space, this is based on the statements provided by people who we consider experts in the field. It is based in their authoritative explanations, and this is what makes us trust them. However, if these experts see reduced their capacity to recollect evidence regarding their field of study, those authoritative explanations will become weak, reducing the trust in their expertise. Thus, we can posit that:

1. We get evidence from people who we consider trustworthy.
2. We consider trustworthy some people regarding only some specific topics.
3. We consider these people experts in those specific topics.
4. That expertise comes from their authoritative explanations regarding the specific topic.
5. To provide authoritative explanations, previous evidence is needed.
6. If there are no changes, it could become highly harmful and/or lethal and/or expensive than ever to recollect the primary evidence.
7. Without primary evidence, there is no authoritative explanation, nor expert, nor reasonable trust.

If there are no changes, it follows that human knowledge would be predictably self-limited due to the lack of current responsibility, although there are other sources of evidence.

It must be added that experts regarding space still can provide evidence through logical or mathematic entailment and also through logically sound or cogent arguments. This appears to be accurate, and this could be done from a rational perspective. It could be done if the entailments and arguments are sustained in premises established in general scientific laws or in data obtained in the past. Nevertheless, this still involves a limitation.

If data obtained in the past cannot be regularly tested, and it is not subject to falsifiability, the knowledge already obtained will potentially not evolve. This is because some kinds of new knowledge, theories, or tools, will not be able to be applied. As a consequence, the new knowledge developed about space will not be able to be tested through different methodologies. A context in which natural or field experiments are limited leads to the sole possibility of laboratory experimentation. Nevertheless, due to the nature of the object studied, this opportunity does not seem to be realistic. Not even in the very long term. Due to this fact, the evidence and potential knowledge that could still be obtained would be too weak to be considered a solid scientific paradigm (Christensen, 1994; Kuhn, 2012). Thus, we can posit that:

1. As humans, we can get evidence from logical and mathematic entailments.
2. We can also obtain evidence from sound and cogent arguments.
3. Although this can be useful, the impossibility of obtaining new data through direct senses or tools correctly calibrated implies a limitation in obtaining new available data.
4. This also implies the impossibility of carrying out natural and field experiments.
5. Due to the nature of the object, laboratory experiments are not possible.
6. Through solely logic, mathematics, or argumentation, the knowledge obtained is weaker than it could be if tested.

If there are no changes, it follows that human knowledge would be predictably self-limited due to the lack of current responsibility.

4. Unsuccessful solutions

4.1 The legal situation

One could reasonably think that this is not a real issue, since probably, after Kessler's contribution, and with the current information available, there are already effective regulations and tools to reduce this debris. One could reasonably think that, since human beings are aware of the future, in the present, a solution is already existing precisely to avoid the potential situation of danger. Nevertheless, this is not the case.

Space Agencies would be legally responsible if a piece of debris felt into your property. At the same time, much of the artificial debris that falls back down to Earth lands in the ocean. The situation is no different regarding the debris still in space. Legally, governments are responsible for their airspace. But their airspace finishes after 100 kilometres vertically from their borders, in Kármán line.

This means that beyond the Kármán line governments do not have any legal responsibility for the debris accumulated there. Moreover, the Fédération Aéronautique Internationale (FAI) requested the International Astronautical Federation (IAF) to reduce the Kármán line to 80 kilometres. (FAI, 2018). This is the line where regulatory bodies divide Aeronautical and the Astronautical responsibilities (FAI, 2017; Haley, 1963; Lyall & Larsen, 2013; Reynolds & Merges, 2021) and a reduction implies even less space with national legal responsibility. In this context, some governments, but not all of them, decided to transfer responsibility to Space Agencies, without, however, obtaining the expected results (Munoz-Patchen, 2018; Sachdeva, 2013).

Currently the situation concerning artificial space debris and the Kessler Syndrome presents analogies with other areas of environmental challenges. Antarctica, for example, is also subject to a lack of international legally binding agreement, which has led to environmental crises. Since Antarctica is a vital component of the global climate system, a lack of intervention and unsustainable practices can result in cascading effects on other parts of the world, demonstrating the interconnectedness of Earth's systems (Rintoul et al., 2018). Another example is marine plastic pollution with its direct environmental impact due to the lack of an international legally binding agreement. As with artificial space debris, lack of intervention and increasingly unsustainable practices can result in water circulation crises, as well as other issues. The water circulation generated by islands of plastics such as the Great Pacific Garbage Patch and the North Atlantic Garbage Patch can impact ocean circulation patterns, potentially altering heat distribution and influencing climate-regulating processes such as thermohaline circulation (Miron et al., 2021).

4.2 Examples of attempts

Since the responsibility for reducing artificial space debris was transferred to the Space Agencies, and, depending on its altitude, the debris needs between a few years and more than a century to disappear, some Space Agencies started thinking in ways to address this issue. To achieve this objective, NASA created the Orbital Debris Program Office at the Johnson Space Center in Houston (Wild, 2021).

However, this commitment has had little success thus far and the quantity of space debris is increasing.

In this respect, the Chinese satellite SJ-21 has applied a pragmatic, but not long-term solution. This satellite has been seen taking debris and simply reallocating it in another place (Pardo, 2022). ESA is planning to launch ClearSpace-1, developed by the École Polytechnique Fédérale de Lausanne, by 2025. This will be a robotic tool with arms to collect multiple objects, but it is not yet operational (EPFL, 2015; ESA, 2019). Indeed, during its first attempt, ClearSpace-1 is expected to take only one single object. (Devlin, 2019). Kounotori, from the Japan Aerospace Exploration Agency, is trying to collect debris using a fishnet system, but is encountering important problems, such as the difficulty of collecting tiny pieces of debris (Phys.org, 2016). The same idea is also being tried out in partnership between public institutions and private ones, such as SpaceX, as in the example of the mission RemoveDebris, which has not yet been able to resolve the issue of the space debris in a significant way (Clark, 2018).

Others have thought of methods to reduce the impact of the artificial space debris without the need of having to travel there. On paper, this proposal seems the most interesting, since it could reduce the problem without involving a hazard for spacecraft and astronauts, although it does not mean that this activity will not have other externalities. Nevertheless, this hypothetical solution, has not yet (Phipps et al., 2012) been implemented.

Thus, we may consider our main hypothesis — if the Kessler Syndrome becomes a reality, human knowledge will be predictably self-limited due to the lack of current responsibility — as logically demonstrated. Moreover, following the sociology of expectations, imaginations of the future shape its development as a consequence of its performative power (Van Lente, 2012, 2021). Expectations shape social behaviour, interactions, and outcomes. This includes technological outcomes. Therefore, it is important to advocate for a future in which technological innovations, economic systems, political processes, and cultural practices, are aligned with developing sustainable expectations regarding cosmos exploration. This will have an impact at many levels, including human ability to gather knowledge via evidence.

5. Conclusions

Artificial space debris is made up of "broken or torn pieces of something larger" with a human origin that are not useful pieces anymore. Many of these pieces are in orbit or in space, while others fall back to Earth. Pieces that fall back into Earth involve a security and an environmental risk, while those remaining in the space could make space exploration highly hazardous and expensive.

Moreover, natural debris is continuously being generated, as well as artificial debris constantly increasing. Technological innovation and price reduction are making space exploration more accessible and frequent. At the same time, there are previsions that in the near future collisions between the already existing debris will be the main source of new space debris.

Humans can be defined as rational. To have rational knowledge, humans need evidence. Evidence can be obtained from different sources that can be classified as: direct evidence using our empirical skills; indirect empirical evidence through a device or tool which is reliably calibrated; the testimony of others in whom we trust; the testimony of experts in that specific area; authoritative explanations; logical or mathematic entailment; and logically sound or cogent arguments.

Due to the current situation, direct and indirect empirical evidence could become too expensive or hazardous to take place. And without direct and indirect empirical evidence, authority, trust, and expertise are built upon a less solid base. Logical or mathematical entailments, and logical arguments, can still be a solid source of evidence regarding space. Nevertheless, the absence of direct or indirect exploration inevitably limits the available data, and its falsifiability through field or natural experimentation.

At the same time, there is a lack of legal responsibilities for the regulation of artificial space debris and scientific trials to modify the situation have not thus far been successful. Because of this, if there are no changes in this situation, human knowledge about space will be self-limited due to the lack of responsibility. Therefore, it becomes imperative to consider sustainable management of Earth's orbit as a common resource, fostering cooperation and responsible practices to prevent exacerbating the problem of space debris. Achieving this goal will require a multi-faceted approach and collaboration among various stakeholders, both at a public and at a private level.

Examples of this collaboration should include the establishment or reinforcement of international binding agreements to govern space activities. These agreements could outline guidelines for satellite design, launch procedures, and end-of-life disposal, ensuring that all entities operating in space adhere to responsible practices. National space agencies, international organizations like the United Nations, and private companies could collectively contribute to the development and enforcement of these regulations.

Identifying the key actors in this endeavour is crucial. Governments, as primary space agencies and regulators, could play a pivotal role in creating and enforcing regulations. Private companies, particularly those involved in launching rockets and deploying satellites, must be obliged to adhere to these guidelines. Organizations such as the International Telecommunication Union (ITU) and the Space Data Association (SDA) could facilitate coordination and communication among the already existing satellite operators to minimize the risk of collisions and debris generation.

Certainly, competing interests over Earth's orbit exist, fuelled by the belief that the potential benefits of space activities are vast and varied. Conflicts might arise between nations vying for orbital slots, companies aiming to secure prime positions for their satellite constellations, and those advocating for conservation of the orbital environment. Balancing these interests will necessitate diplomatic negotiations, transparent allocation mechanisms, and compromise.

A possible development is the establishment of quotas for new rocket launches and satellite deployments. These quotas must be scientifically determined, considering the capacity of the orbital environment to accommodate additional objects without escalating the debris problem. The specific timeline for implementing such quotas will depend on a thorough assessment of the current state of orbital congestion and the rate of space activity growth.

In conclusion, transforming Earth's orbit into a sustainable common space requires global cooperation, comprehensive regulations, and the active involvement of governments, international organizations, and private industry. By establishing guidelines, allocating resources responsibly, and addressing conflicting interests, we can mitigate the impact of space debris and ensure that future generations can continue to explore and benefit from the vast frontier of space. Sustainability science must advocate for the responsible stewardship of this shared resource to enable a brighter and more sustainable future for space exploration, and thereby human knowledge.

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