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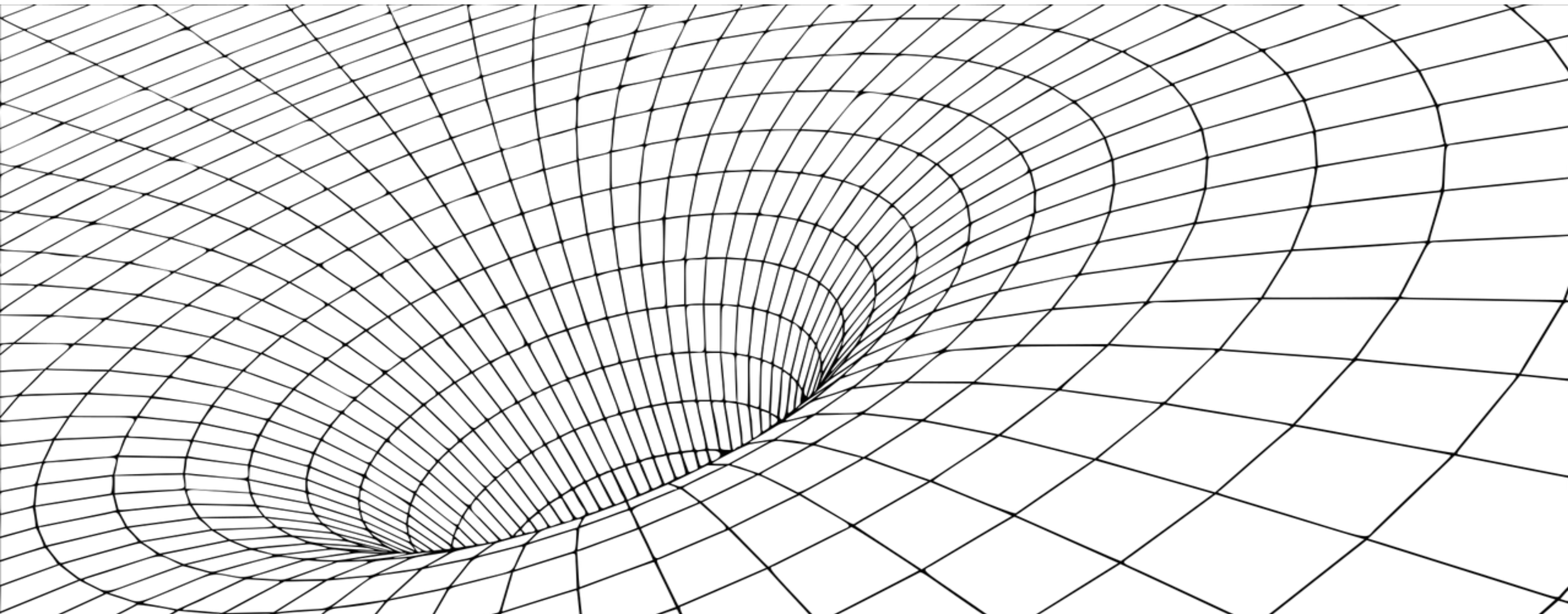

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THE FOUNDATIONS OF THE ECONOMICS OF THE OUTER SPACE: A PREMIER OVERVIEW

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Abstract: Although it is probably too early to define a new field of economics named "Economics of the Outer Space", the rising importance of outer space for scientific, economic, and social development is beyond discussion. Nowadays, commercial satellites offer various vital services to Earth's consumers at the cost of congesting and polluting space with orbital debris. However, this is just the beginning of history, and several new commercial exploitations of outer space will appear in the future, with the consolidation of an almost autonomous industry in space, further congesting and producing further market failures. This paper reviews seminal and initial works in this new field and discusses the connection with existing well-established fields in economics. Human activities in outer space involve several economic and legal issues related to regulation and property rights, congestion, pollution, militarization and weaponization, and exploitation of natural resources. These issues should be addressed as soon as possible to mitigate conflict among spacefaring agents and loss of welfare for humankind. Finally, we suggest future research directions in this promising and highly unexplored research area.

Keywords: Outer space; Satellites; Earth’s orbit; Orbital debris; Anti-satellite weapon systems; Space industry; Satellite data.

1. Introduction

Since the beginning of time, humans have been fascinated by the Universe. Nowadays, outer space has become a new and vital environment for commercial, scientific, and military activities. In the foreseeable future, humans will colonize space, extending the limits of the Earth to human life, and there are already some embryonic plans for the creation of colonies in the Lagrange points, the Moon and other natural satellites, and Mars. Spacecraft developed during the 20th Century are, in a way, equivalent to the wooden ships that allowed the Vikings and Christopher Columbus to cross the Atlantic Ocean to discover the "New World". Technological progress, combined with curiosity and need to understand, and desire for exploration and economic exploitation of outer space will pass over the economic frontiers imposed by the geophysical limits of planet Earth, expanding the finite endowment of natural and energy resources. This will lead to the development of new technologies and new goods impossible to be produced in the Earth, all of them leading to profound economic and social changes that are yet to be established.

Although human exploration and economic exploitation of the outer space is relatively recent (first human-made spacecraft successful launch occurred in 1957), several market failures and other troublesome economic, legal and political issues are arising at a rocket speed as commercial, military, and scientific activities in the space are in continuous expansion. No agent (national governments or international organizations) has authority over property rights of the space, except spacecraft ownership, and therefore, human activities in the space, excluding current commercial satellites orbit location and electromagnetic spectrum in GEO orbit,[1] are not subject to any centralized regulation or property rights scheme, being an example of a multidimensional extra-terrestrial common pool resource. In this environment, outer space exhibits the characteristics of a global common resource, and hence, subject to comparable economic failures than other international commons in the Earth (i.e., fisheries in international waters, high seas sailing, the atmosphere, or the Antarctica). However, physical characteristics of outer space are different to the ones existing in the Earth (vacuum, near zero gravity, extreme temperatures, etc.), and heterogeneity of outer space resources are key conditioning factors that would introduce new challenges in organizing human activities in the outer space. The only international agreement that stablished a list of basic principles to regulate human activity outside the planet Earth is the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies", simply referred to the Outer Space Treaty (OST). The OST enumerates a list of basic principles for human activity in the outer space to be followed by nations (not private companies as the Treaty was signed in 1967 where only governments had the technology and financial resources to access the space), including freedom of access and exploration, no sovereignty, and peaceful purposes. The basic principles of the OST have been later extended by several agreements and conventions

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[1] Geostationary (GEO) orbit is a particular orbit also referred to as a (circular) geosynchronous equatorial orbit (GEO) at 35,786 km in altitude above Earth's equator. An object in such an orbit has an orbital period equal to Earth's rotational period, one sidereal day, and so it remains in a fixed point to the Earth. This is an excellent advantage for satellite communication, navigation, positioning, and weather observation. In short, Earth' orbit is divided in Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and GEO.

on more specific issues. However, the principles instituted in the OST represent a set of basic rules with a minimal scope to which countries pursuing activities in the outer space are subject, and it cannot be considered as a full-operational regulatory framework but where the "first come, first serves" principle seems to dominate.

Although it is probably too early to define a new field of economics named “Economics of the Outer Space”, the rising importance of the outer space for economic and social development is beyond discussion. Nowadays, satellites and other spacecraft offer a variety of critical services to Earth’s consumers, including broadcasting and telecommunications services, internet, positioning services, Earth observation and remote sensing, etc., apart from scientific and vital defence and security activities. However, this is just the beginning of the history, and several new forms of commercial exploitations of the outer space will appears in the next future with the development of a highly autonomous in-orbit industry.

Given technological advances in spacecraft manufacturing and launching systems, and the increasing presence of humans in the outer space, the outer space is becoming the new economic frontier (Weinzierl, 2018). In the initial stages, space exploration was conducted by countries, mainly by the U.S. and the Soviet Union, given the existing technological and financial barriers. However, reductions in costs and development and access to new technologies have dramatically democratized access to the outer space, increasing the number of spacefaring nations and private commercial operators. Indeed, a large variety of industries are expected to be developed in the near future, additional to the industries that are already well established, other than military and scientific activities. Industries such as space manufacturing of special goods for customers on Earth using microgravity, vacuum and extreme temperatures (Patel, 2019), in-space manufacturing and maintenance and repair services (Prater, Werkheiser, and Ledbetter, 2018), asteroid mining (Ross, 2002), or space tourism (Peeters, 2010), among others, are expected to be developed in the foreseeable future, further congesting outer space and generating more space pollution. Meanwhile, the strategic value of outer space for defence and security issues is expanding rapidly, increasing the militarization and weaponization of space, and transforming the outer space into a potential battlefield for main powers.

All these transformations raise several troublesome issues that demand attention by economists as these transformations will have an increasing importance for economic and social development of humankind. Whereas most of these issues have an economic nature, the outer space has received little attention by economists. This contrast with other fields, such as law, where considerable efforts are being made to assess the legal implications for managing human activities in the outer space. Human activities in the outer space involves several current and incoming economic issues, related to property rights, markets regulations, orbit slots, congestion, pollution, and exploitation of natural resources, that should be addressed as soon as possible to mitigate conflicts among spacefaring agents and loss of welfare for the whole Earth planet.

The seminal foundations for the economics of outer space were constructed by O'Neill (1977) and Sandler and Schulze (1981). O'Neill (1977) was the first to study the feasibility of space human colonies from an economic perspective. The path-breaking contribution by Sandler and Schulze (1981) enumerated and studied a few economic issues related to commercial and other activities in outer space, including broadband spectrum, rights over the geostationary orbit, and the risk of collision of human-produced objects. However, from these seminal contributions and somewhat surprising, little advance has been observed in the economic literature in the study of human activities in the outer space until recently, despite the critical economic issues arising in this high-value environment, that can put at risk future benefits for mankind from exploration and exploitation of the outer space.

The main objective of this article is to review advances in this direction and bring to the economic analysis forum the necessity to pay attention to what is happening in the outer space. The focus of the paper is twofold. First, this paper identifies a few heterogeneous economic issues related to human activity in the outer space. Second, the paper overviews how an incipient economic literature has dealt with them, detecting leading contribution laying the foundations of this new field in economics, including topics from regulation to pollution, and from natural resources to defence economics. This new field of study will be somehow connected with many existing well-established economics fields such as production and capital accumulation; automation and technological change; collective decision-making; public economics and international public goods; natural resources; environmental economics; international trade; national security and defence, data for measurement of economic activity and policy evaluation, among others. Existing economic analysis tools and techniques can be applied to the study of this "new economy", which shares some similar characteristics to other standard markets in the Earth, but also presents some distinct and special features, given the physical characteristics of outer space, that will demand new models and alternative approaches which combines economics modelling with some physical and space models, in a similar fashion to what it is observed in recent advances in the fields of energy and environmental economics. The high velocity of space technological progress and the milestones achieved in recent decades, along with the important economic implications of the outer space conquest, demand an urgent attention by economists before market failures would reach an unsolvable threshold leading to permanent welfare losses for the entire mankind, and the dawn of political and security conflicts of a global nature.

Along the rest of the paper, we will review some key selected topics on the economics of the outer space, discussing their connection with existing fields in economics.[2] Section 2 presents some data about the importance of the outer space sector from a physical and economic perspectives. Section 3 focuses on the global regulatory framework for human activities in the outer space and describes some characteristics of the outer space as an extra-terrestrial global common pool resource. Section 4 focuses on congestion problems related to orbit and spectrum. Section 5 explores one of the issues that is attracting more attention by economists: space pollution in the form of orbital debris. Section 6 explores several industries, including in-orbit manufacturing, asteroid mining, orbital services, etc., which are incipient but with great development potential. Section 7 focuses on the use of the space for security and defence, and the consequences of the increasing militarization of the outer space. Section 8 deals with the application of data collected by Earth's observation satellites to measuring economic activity and economic growth. This

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[2] Interstellar trade, tax, and finance literature, pioneered by Krugman (2010), is deliberately not covered in this survey.

is a promising avenue that can dramatically transform the way how applied economics is conducted as availability of economic data would be increasing, with higher frequency data and new spatial units. Finally, Section 9 collects the main conclusions and puts forward some suggestions for future research directions in this promising and highly unexplored research area.

2. Basic data

Human exploration of the outer space started in 1957 with the first successful launch of an artificial satellite (Sputnik I) into orbit. This initial launch fuelled a space race between the U.S. and the Soviet Union, the only two countries with enough financial resources to produce the necessary technology to insert in the Earth's orbit a human-made spacecraft at that time. Sixty years later, the number of spacefaring nations has increased to twelve nations and a regional space organization, the European Space Agency (ESA) that include another 22 countries, that have indigenous launch systems, nations with own satellites have increased to 83, there are 13 private satellite operators, whereas the number of private companies with own orbital launch systems is of seven.

All this expanding human activity in outer space has resulted in a large number of humanmade objects traveling at high speed in the Earth's orbit. Orbit is not only populated by operational satellites and other spacecraft, as space stations, but also by derelict dead satellites, rocket bodies, and a large variety of orbital debris produced from launching operations, breakup and explosion of satellites and rockets engines, collisions between operational satellites and orbital debris, and even fragments intentionally produced by anti-satellite military tests.[3]

Table 1 shows some key data about human activity in the Earth's orbits and the number of orbital debris, as estimated by the ESA (European Space Agency) in December 2023. Since the beginning of space exploration, a total of around 6,500 successful launches have been realized. This figure is not equivalent to the number of spacecraft placed in orbit (about 16,990) as a launch can include more than one satellite or spacecraft. Indeed, the relationship between launches and new satellites in orbit is changing dramatically in the last years due to new varieties of small and micro satellites and launch systems' higher power and payload capacity. The number of satellites in Earth orbit is over 11,500 of which about 9,000 are operational. The total number of pieces of debris tracked by the United States Space Surveillance Network (SSN) is 35,150. The number of registered incidents, including break-ups, explosions, collisions, or anomalous events resulting in fragmentation, is more than 640. The biggest incident was the collision on February 10, 2009, of an active US communications satellite (Iridium 33), with a defunct Russian military communications satellite (Kosmos 2251). Both satellites were destroyed in the collision, producing a total of around 2,200 pieces of new tracked debris with a size of at least 5cm (NASA, 2007). However, the most important incident was intentional (an anti-satellite military test), resulting in the destruction of the Fengyun-1C (a Chinese satellite) on January 1, 2011, by a kinetic weapon producing an estimated 3,037 pieces of new

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[3] As defined by NASA, orbital debris is any human-made object in orbit that no longer serves a useful purpose, including spacecraft fragments and retired satellites.

tracked debris. Most of the activity takes place at Low-Earth-Orbit (LEO, between 200 and 2,000 km), and at Geostationary Orbit (GEO, at 35,786 km).

Table 1: Basic data of activity in outer space

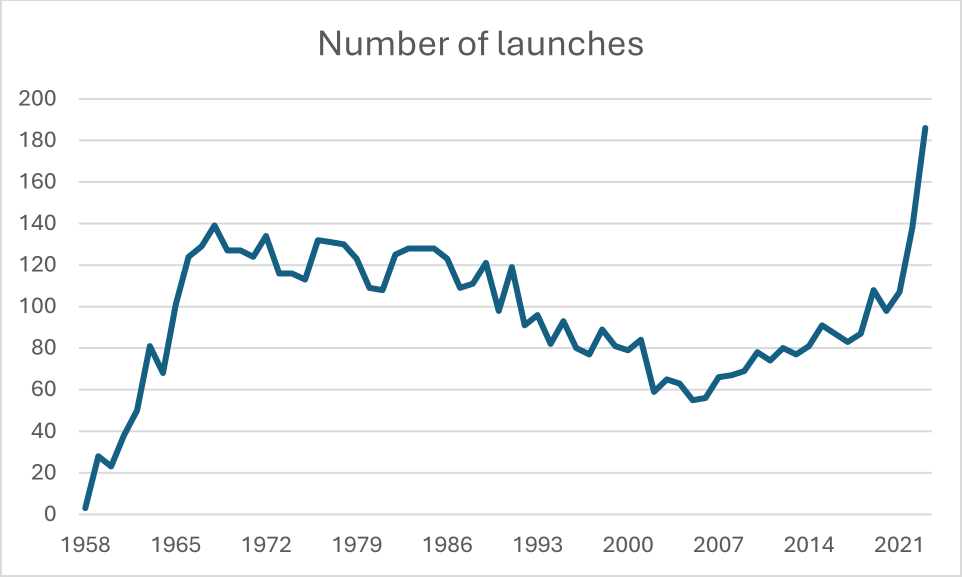
Successful launches	6,500
Successful satellites launches in Earth orbit	16,990
Satellites in Earth's orbit	11,500
Operational satellites	9,000
Debris tracked by SSN	15,150
Incidents resulting in fragmentation	640
Debris > 10 cm	36,500
Debris between 1 cm and 10 cm	1,000,000
Debris between 1 mm and 1 cm	130,000,000

Source: ESA (December 2023)

The standard classification of orbital debris is a function of its size and on the technical possibility of tracking it. Projections obtained using different evolutionary models for debris dynamics population (for example, the LEO-to-GEO NASA's Environment Debris Model, LEGEND) have estimated amounts of around 34,000 pieces of debris larger than 10cm diameter, 900,000 objects between 1cm and 10cm, and over 128,000,000 fragments between 1 mm and 1 cm. The number of debris objects estimated by the MASTER-8 model (the ESA's Meteoroid And Space debris Terrestrial Environment Reference model) is of 36,500 objects larger than 10cm, 1,000,000 fragments greater than 1cm to 10cm, and 130 million fragments greater than 1mm to 1cm. The destruction power of debris smaller than 1 cm is estimated to be low and non-fatal in the case of a collision with a satellite. However, debris larger than 1cm is potentially deadly due to the high velocity of the impact (between 5 and 10 kilometres per second).

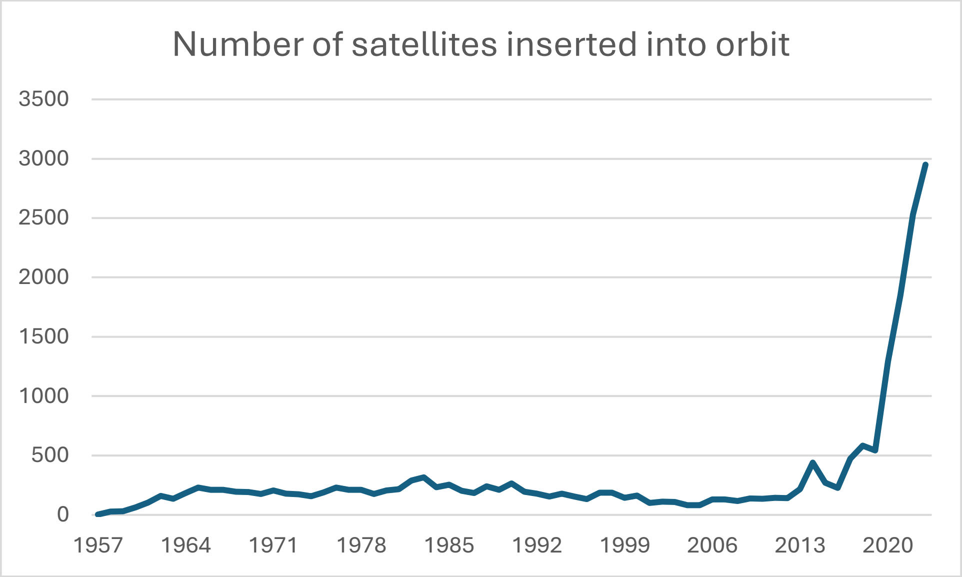
Figure 1 plots the number of launches per year, using information from the DISCOS database and the Union of Concerned Scientists (UCS) satellite database. In the first years of space exploration, the number of launches increased rapidly due to the space race between the United States and the Soviet Union. From 1968 on, the number of launches stabilized, and even started to decrease. The trend returned to be positive from 2005, with a trend-break in the last two years 2022 and 2023, due to private firms' activity and the launching of satellite constellations. Figure 2 plots the number of satellites inserted into orbit. Figures are different to launches given that each rocket can carry several satellites. Indeed, we can observe how the number of satellites per launch has dramatically increased in the last year. More powerful launches vehicles together with the reduction in the size and mass of satellites explain those figures.

Figure 1: Number of rockets launches per year (1957-2023)



Source: UCS, DISCOS

Figure 2: Number of satellites inserted into orbit (1957-2023)



Source: UCS, DISCOS

Figure 3 shows how the total number of catalogued objects in orbit has evolved over time (the number of debris is larger than the number of catalogued objects; the US Space Surveillance Network (SSN) can only track objects larger than 5-10cm in LEO and larger than 30cm to 1m in GEO, and only objects with a known origin are catalogued). Some jumps in the number of objects can be observed in some years, caused by accidental break-ups, explosions, and collisions, but also by the deliberate destruction of targets in anti-satellite (ASAT) tests. The number of catalogued objects has been increasing steadily, except in some years such as 1989 and 1990, coinciding with the disintegration of the Soviet Union, which significantly decreased the number of launches. The decline of the total number of objects in orbit in these two years was due to the fact that de-orbit, both intentionally and by atmospheric drag, was larger than the new objects in orbits from launches and other sources. However, the creation of debris has accelerated in the second half of the decade beginning in 2010, and in the last three years due to both collisions with debris and additional ASAT tests. Figure 2 plots the number of new catalogued objects in orbit yearly, with significant increases in the last two decades. There are three main reasons for this. First, there is an increasing number of accidental collisions between satellites and debris (the most important has been the collision of a commercial American communication satellite, the Iridium-33, with Cosmos 2251, a derelict Soviet Union military satellite, on February 10, 2009). Second, the number of ASAT tests involving the physical destruction of the target has increased significantly during the last two decades, as the number of countries with this type of weapon system has expanded. Third, tracking technology is constantly progressing. The Space Fence radar of United State Space Force (USSF) becoming operational in March 2020 has increasing the capability of tracking and accurate measurement of space objects. Finally, the number of new catalogued objects in orbit will experience significant growth in the next years with the advent of constellations of satellite at LEO. As of August 2002, the SpaceX Starlink constellation has over 2,793 operational satellites (of 3,055 launched) from a planned total of 12,000 satellites by 2026 (Berry, 2022).

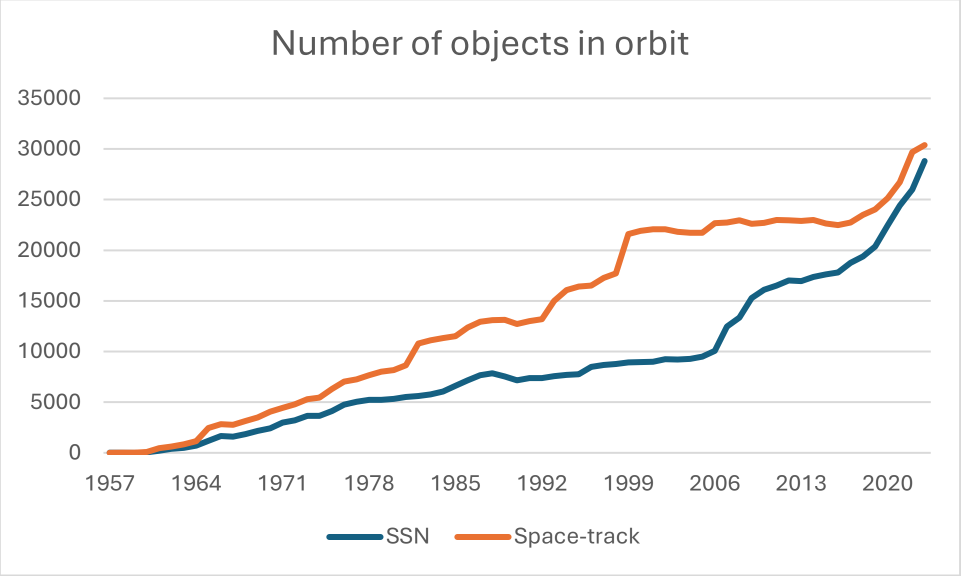


Figure 3: Catalogued objects in orbit 1957-2021. Source: US Space Surveillance Network (SSN), and Space-track.org

Apart from the increasing number of satellites and other spacecraft in orbit, the economic impact of the space industry has continued growing at high rates. Weinzierl (2018) advanced that commercial activities in space generate around $300 billion in annual revenues. Whealan-George (2019) using input-output tables for the US economy estimates an economic impact of commercial space industry of approximately $38 billion or 2.0% of total U.S. GDP, accounting for 195,484 full- and part-time jobs for the year 2016. The Bureau of Economic Analysis (BEA, 2023) estimates that space industry contributed to 129,9 billion dollars to the US economy in 2021 (0.6% of GDP), with a total of 360,000 full- and part-time jobs in the private space industry. Space Foundation (2023) estimates that the global space economy has an impact of $546 billion dollars for the year 2022. Considering that the US GDP is around 25% of World GDP (using nominal GDP data from the World Bank), space economy would be a 0.63% of world GDP. The Satellite Industry Association (SIA, 2023) estimates that the global space economy accounts for $384 billons for the year 2022, around a 0.45% of global GDP. According to the estimates, quantitatively the space economy is still a relatively small fraction of the whole economy, although some services provided by satellites are vital for consumers. Corrado et al. (2023) explore the connections between the space economy and economic growth, measuring space activity spillovers. They find that space activity spillovers are of high magnitude although with a negative trend over time. Adilov et al. (2023a) estimate the value of a total of 3,369 satellites in orbit in 2020 as a function of their mass and the expected cost of satellites losses by collisions. They estimate a value for satellite assets between 181,618 and 217,942 million of dollars, and an expected losses between 85,97 and 103,15 million dollars. Adilov et al. (2024) extend previous estimations to different orbits, with economic losses concentrated in the low-Earth orbit (LEO).

3. Regulation and property rights: The outer space as a global common pool resource

A significant economic challenge associated with human activity in outer space is related to the global regulation of this environment, particularly concerning property rights over natural objects and other space resources. Martin-Lawson et al. (2024) consider that outer space is an Area Beyond National Jurisdiction (ABNJ) region as oceans, polar regions and the cyberspace. Whereas some advanced has been done in the law literature, little if not none, have been done in economics to assess the implications of a regulatory framework for current and future activities in the space, apart from the contribution of Weeden and Chow (2012). Outer space displays the characteristics of a global common pool resource, making it susceptible to similar economic failures observed with other international commons on Earth. However, it also possesses unique attributes due to its distinctly different physical environment compared to that of Earth. In their “The Economics of Outer Space”, Sandler and Schulze (1981) surveyed some economic issues related to the outer space; they acknowledge the access to outer space for human activities as a common property resource, like the high seas.

Technological progress has democratized access to space, leading to an increase in the number of countries and companies operating satellites. However, the capability to launch satellites and spacecraft into orbit remains limited to a few spacefaring entities. Excluding a specific entity from using outer space is challenging, if not impossible, although this could change with further technological advancements. Considering the anticipated regulation of outer space activities and the political dynamics involved in such regulatory processes among spacefaring nations, it is crucial to examine various economic questions related to this issue. Property rights in the outer space will be a source of conflicts among central spacefaring nations. Outer space exhibits a “subtractability of use” characteristic, similar to other common resources. Problems arise with issues such as protecting human lunar heritage, which would imply property rights over the place where lunar missions are carried out by the U.S., the Soviet Union and China (Herzfeld and Pace, 2013).

Regulatory challenges have been evident from the early days following the initial exploration of outer space, prompting the international community to establish the International Telecommunication Union (ITU) as an independent authority. This body was tasked with spearheading the development of regulations for space activities and launches. The issues have been studied from both legal and economic perspectives in scholarly literature. While a detailed survey of the legal perspective is beyond the scope of this paper, significant contributions in this area are worth noting. Among these is the book "Space Law: A Treatise" by Lyall and Larsen (2018), now in its second edition, which provides a coherent and comprehensive examination of outer space from a legal standpoint. The treatise not only discusses the role of the ITU but also addresses developments across all space applications, including Low Earth Orbit (LEO) activities such as space tourism and Geostationary Orbit (GEO) activities like telecommunications and finance. In addition to the general coverage provided by international space law, there now exists a specific body of law known as Orbital Law, which deals with legal issues unique to the exploitation of Earth's orbits. As Blount (2022) explains, this legal framework addresses resource allocations, potential conflicts, and established coordination mechanisms, offering a focused legal analysis of the challenges presented by the unique characteristics and critical importance of Earth's orbital environments.

The Outer Space Treaty (OST), formally known as the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies," is the sole international agreement that establishes a set of basic principles for regulating human activity beyond Earth, aside from ITU regulations concerning GEO commercial activity. Drafted in 1967, when only nation-states had the technological and financial capacity for space exploration, the OST outlines fundamental principles to be adhered to by these nations. These include freedom of access and exploration, a prohibition on claiming sovereignty, and a commitment to peaceful purposes. Property rights, except for spacecraft ownership, are explicitly excluded under the OST. While the basic principles of the OST have been expanded upon by subsequent agreements and conventions addressing more specific issues, they represent a rather limited set of rules that govern activities in outer space, and do not constitute a comprehensive regulatory framework. The prevailing "first come, first served" approach highlights the inadequacies of current regulations. The consequences of this regulatory shortfall were articulated by Hardin (1968), who famously argued that "Freedom in a commons brings ruin to all." However, Ostrom (2010) later demonstrated that it is possible to avoid the "tragedy of the commons" without resorting to privatization or heavy-handed government regulation. Yet, it remains unclear whether the unique physical characteristics of outer space necessitate a powerful sovereign or, conversely, if outer space should remain a realm of minimal governance.

Outer space presents an ideal setting to explore the governance possibilities suggested by Ostrom (2010). Macauley (2003) argues that regulation is suitable for certain outer space resources, but not for others. Weeden and Chow (2012) explore the potential applications of Ostrom’s principles for managing outer space to circumvent both privatization and centralization. They advocate for the adoption of "adaptive governance," as proposed by Dietz, Ostrom, and Stern (2003). Their research assesses the applicability of the eight principles outlined by Ostrom (1998) to near-Earth orbit, which they liken to parking garages, exploring how these principles could be adapted to this unique context.

Finally, a related issue stems from the lack of defined sovereignty limits in space. This challenge originates from the difficulties in establishing precise boundaries for a country's airspace. Theoretically, outer space begins at an altitude of approximately 100 kilometers (the Kármán line). However, in practice, the boundaries of a nation's airspace sovereignty are often determined by the range of its air defense capabilities. Proper regulation of these limits is crucial to prevent future conflicts as air defense technologies evolve.

From an economic perspective, it is crucial to recognize that the Outer Space Treaty (OST) currently conflicts with the planned commercial exploitation of outer space resources, such as asteroid mining. When the OST was originally signed, only nation-states were capable of space exploration, and no private companies had access to space. This context underscores the necessity for a comprehensive revision of the OST in the coming years, with economic considerations playing a central role in shaping future treaties. As Weeden and Chow (2012) have highlighted, outer space comprises a variety of common pool resources, each with unique characteristics that necessitate a tailored governance framework.

4. Congestion in the outer space: The market for orbits and electromagnetic spectrum

A problem arising from the absent or under-regulation of the outer space global common is over-use of some space resources. Space around the Earth is vast but not infinity. Present commercial and military activities in the outer space in the form of satellites and other spacecraft is not uniformly distributed at different altitudes but are concentrated in certain orbits of high value for technical reasons. This is the case of geostationary or geosynchronous equatorial orbit, where communication, weather observation, and positioning and navigation satellites are allocated, as at that particular altitude they are in a fix position with respect to the Earth. On the other hand, a distance between satellites is required to avoid electronic interferences. Spectrum frequencies and orbital slots are assigned by an international agency: the International Telecommunication Union of the United Nations (ITU). The allocation is done on a first come, first served principle and it is costless and unlimited in time, except for some restrictions on the period between the permission approval and the actual moment in which the satellite must be in orbit and operational. Although it establishes some rules, ITU has no actual enforcement power on spacefaring actors and therefore space activities basically occur in a highly non-regulated market.

With the development of technology (access by private firms, satellite constellations, space mining firms, etc.), the under-regulation is rapidly bringing to overusing outer-space resources as we would expect in any tragedy-of-the-commons situation. In the case of the outer space, resources are transmission frequencies and, perhaps surprisingly, the space itself. This occurs because interested parties – essentially commercial firms and military agencies – mostly want satellites and other spacecrafts to be fixed above the same position over the Earth. This can be achieved either with continuous positioning manoeuvres that are clearly over costly in terms of fuel and operational life, or by positioning devices in very specific orbit slots called Geostationary or Geosynchronous Equatorial Orbits (GEO). Here the cross-gravity of celestial bodies in the solar system combined with velocity establishes an orbital period that exactly matches Earth's rotation period, thus maintaining devices constantly above the same point over Earth's surface without running engines. Communication, weather, GPS are examples of satellites positioned in GEO orbits, which are located at an altitude of approximately 35,700 and have a radius of approximately 42,000 kilometers. Available slots at GEO are relative abundant but not infinite, also considering that satellites require a minimum distance between each other to avoid electronic interferences (maximum number of slots are limited depending on the safety distance between satellites). Indeed, in some places there is no more free slot for additional satellites. Hence, the number of satellites that can operate contemporaneously in GEO is limited. Slot rights are given for the operational life of the satellite, but typically operators can replace old satellites by new ones, and hence, rights are indefinitely in practice, which would imply a barrier to new entrances.

From an economics perspective, the first analyses the market of satellites appeared in mid-seventies, typically pursuing approaches on costs minimization. Snow (1975) applied a model of investment cost minimization to the case of satellite communications. He used INTELSAT data to calibrate the model and obtain the optimal planning of investment in satellite capacity and replenishment times. Early et al. (1978) also used INTELSAT data to analyse the amount of R&D required to support a satellite communication system and related this expenditure to the determination of hardware investment costs. The authors also provided a proper economic optimization to determine the most profitable station size for new entrants in the INTELSAT system, i.e., they compared small stations with lower initial cost but higher space segment expense as opposed to large station with higher initial cost but lower space segment expense. Early et al. (1978) were the firsts to acknowledge the interest in treating orbits and satellites with proper economic analyses, given that "*The economic viability of these systems is no longer questioned. Instead, new questions relating to system optimization* […] *are of increasing interest*". In this line, Pritchard (1981) provided estimations on the costs of satellite communications systems and some insights on how to minimize such costs. In particular, he acknowledged the relationship between satellites systems costs and some features of satellites design, and suggested to decide on construction design, e.g., satellite lifetime and effective radiated power, as to minimize such costs.

The possibility of congestion in the outer space was first conjectured in the economics literature during the 1980s by Sandler and Schulze (1981). They discussed allocation problems because of externalities and public good problems related with outer-space activities. As an example, they constructed a formal economic model for optimal allocation of telecommunication satellites and examine the efficiency of the existing institutional structure. posed questions about congestion. Wihlborg and Wijkman (1981) also treated space as a common pool of resources and conjectured about congestion problems in geostationary orbits. They suggested to use market mechanisms to allocate efficiently resources in space and compared the first-come, first-served regime with squatters'-right vs. auction regimes. They also argued about the efficiency of these regimes as compared with the proposal to carve up space resources and distribute the parts among nations. At the time, there were less than one eight of the maximum number of satellites in orbit, and therefore their analysis remained theoretical and speculative, even though pioneers and forward-thinking. In fact, sometime later the view of orbits as a finite common pool of resources subject to pollution and congestion was embraced in law journals.[4] Levin (1982) invoked a proper economic analysis of the values of radio spectrum and geostationary orbits, and Levin (1984) propose a political economy plan to allocate orbit resources through mechanisms designed to introduce market incentives. Finally, Macauley (1986) studied the effects on technical change of rationing the usage of the electromagnetic spectrum for communications satellites by the Federal Communications Commission (FCC).

The debate for an efficient allocation of orbit slots and spectrum fully took off in the 1990s, when the focus of the literature shifted from the first conjectures on market mechanisms to allocate efficiently spectrum and orbits to a proper treat of the outer space as a common pool of resources. The change of perception and the urge for regulations were possibly triggered by some events that took place during the 1980s like the increasing number of telecommunication satellites in orbit, the case of Tonga and the case of equatorial countries. These events acknowledged the economic, environmental and social issues implied by human activities in the outer space and stimulated a new branch of the literature. Levin (1988) discusses various proposals to create an international commodities market for spectrum frequencies and then to auction off the rights to use them. Levin (1991) extends previous framework to the possibility of trading rights to orbital slots and spectrum. From Thompson (1996) we learn that a few years later space scarcity and satellites congestion were already taken as starting point for a discussion on Earth's orbits, which in the case of Thompson hinged on fairness and ethical considerations of leaving orbit permits to market dynamics. He argued that the consequent price for orbital slots that would be set in a non-regulated market would put orbits "out of the range of all but financial behemoths". He also discusses the case of Tonga as example of malpractice with space resources. This country applied for the assignment of sixteen free slots from ITU with no intention of using them but only to open an auction for their annual renting. While Thompson was invoking more fairness principles in the centralized allocation, at the same time "an extensive economics literature alleges that the nonmarket administrative allocative procedures now in place are highly inefficient" as noted by Macauley (1998), who developed a computerized model to estimate the economic value of communications satellites at geostationary orbit and the welfare cost of existing non-market administrative allocative procedures. In the same line, Shibusawa (1999) proposed a conceptual model to optimize the location of telecommunication satellites by using maximizing social welfare in terms of utility as in standard economics models and accounting for the negative externalities of satellite congestion. Shibusawa's model differed from the models used in contemporaneous literature to treat satellites congestion only because it was static and did not include dynamic effects of orbital debris.

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[4] The NYLS Journal of International and Comparative Law and the Michigan Journal of Comparative Law.

Although the economic literature studying this issue is limited, some work has been done in this direction. Snow (1975) and Pritchard (1981) are early attempts to apply economic analysis to the market of satellite services. Macauley (1986) studied the effects on technical change of rationing the use of the electromagnetic spectrum for communications satellites by the Federal Communications Commission (FCC). Macauley (1998) focused on the analysis of communications satellites at geostationary orbit and estimates the welfare cost of existing non-market administrative allocative procedures. A more recent contribution is Adilov et al. (2019) who show that incumbent satellite operators have incentives to non-utilizing a fraction of their assigned spectrum and orbital slots. Indeed, these operators have incentives to keeping non-operational satellites in orbit as a barrier to entry for other operators, increasing prices and reducing output and social welfare.

During the first two decades of the XXI century, the rise of the New Space – a novel era for space missions in which private companies in the US took over the NASA in launching rockets and providing space services (e.g. putting satellites in orbit, launching devices and telescopes for space exploration and missions to resupply the ISS) and more countries like China and Europe stepped up as reliable players in the space race – gradually shifted the interest of the economics literature from satellites congestion and the optimal regulation of orbits and spectrum assignments to more practical matters like space debris in the established absence of any coordination. The literature on debris will be analysed in next section, but a few papers are worth mentioning here given their focus on the regulatory aspects of satellite congestion. Macauley (2004) offered an introduction to the variety of ways in which economics can contribute to understanding the value of space. In its third section, he specifically focused on space as a natural resource subject to scarcity and how its scarcity might be managed to best exploit its economic benefits. Weinzierl (2018) effectively illustrated the paradigm shift of the New Space and lay down the main aspects of an analytical economics framework for understanding and managing the development of space economy. He elaborates further by listing three main components that such framework should possess: "*1) establishing the market through decentralization of decision making* […], *2) refining the market through policies that address market failures* […], *3) tempering the market through regulation in pursuit of social objectives.* In this perspective, Adilov et al. (2019) show that incumbent satellite operators have incentives to non-utilizing a fraction of their assigned spectrum and orbital slots. Indeed, these operators have incentives to keeping non-operational satellites in orbit as a barrier to entry for other operators, increasing prices and reducing output and social welfare. Adilov et al. (2023b) proposes to issue interest-bearing performance bonds to provide an incentive mechanism for deorbiting satellites with minimal effect on firms' operating costs.

Further work remains to be done in this area, studying the market for satellites from an industrial organization and strategic commercial policy perspectives, considering that several private firms planned to insert in orbit thousands of satellites (satellite constellations) that will increase congestion further. Constellations of satellites will exponentially increase the number of satellites in LEO. LEO is the most congested orbit but also the orbit with the better physical characteristics to eliminate debris and derelict satellites.

5. Pollution in the outer space: Orbital debris

One of the issues that has attracted more attention from academics in different disciplines, including economists, is the space-market failure leading to the generation of space debris. As defined by NASA, "orbital debris is any human-made object in orbit that no longer serves a useful purpose, including spacecraft fragments and retired satellites". Debris is a type of space pollution, with some particular characteristics different to other type of pollution in the Earth, that could have dramatic consequences for commercial and other activities in outer space (Liou and Johnson, 2006). Launching satellites and carrying out other operations in orbit generate debris that can collide with operational artificial satellites, with fatal consequences in some cases. Even small debris with little mass can have catastrophic consequences for the affected spacecraft due to high velocities. On the other hand, space debris is self-propagating, as collisions between pieces of debris create more debris. This is the so-called "Kessler syndrome" representing a scenario of collisions in cascade (Kessler and Cour-Palais, 1978). Debris is generated from different sources, including parts of launch vehicles and rocket bodies, non-functional satellites, the breaking-up of satellites and rocket bodies, and even tools lost by astronauts.

Traditional launch systems consist in three or four stages, each one with specific engines. Initial stages usually burn in the re-entry to the atmosphere, but last states can remain in the space for long periods, especially for insertions at high altitude orbit. The main cause of in-orbit explosions is related to residual fuel that remains in the tanks of rockets' upper stages or derelict satellites abandoned in orbit. The extreme conditions in outer space quickly cause mechanisms and devices to deteriorate, leading to leaks mixing fuel components, which provoke accidental explosions that break-up rocket bodies and other spacecraft, and generate a large number of fragments that travel around the initial orbit at hyper-velocity (above 10,000 kilometer per hour). Besides such accidental break-ups, spacecraft interceptions by surface-launched missiles have been a major contributor in the recent past. A single event, the intentional destruction of the Chinese Feng-Yun 1C satellite by a missile in January 2007, increased the trackable space debris population by 30% (OECD, 2020). Most debris (around 85%) is at a Low Earth Orbit (LEO) altitude (below 2,000 kilometres), with peak concentration around an altitude of 700-900km (NASA, 2020).

Seminal papers studying the economic consequences of orbit debris are Adilov, Alexander and Cunningham (2015, 2018) and Macauley (2015), followed by Rao, Burgess and Kaffine (2020) and Rouillon (2020). Leaving aside several differences, they have in common to construct stylized physical models, formalizing the dynamics of the populations of orbiting objects, and study the behavior of space industry players, assuming that they neglect their contribution to the proliferation of debris. Adilov et al. (2015) developed a Salop-type model (Salop, 1979), for comparing the optimal number of launches in a decentralized versus a centralized market. Firms can enter the market by placing one satellite in orbit in the initial time, in order to sell satellite services for two periods, unless their satellite is destroyed by collision before. They compare the number of launches in a market equilibrium, relative to the socially optimum. They found that the numbers of satellites and launches are higher than the social optimum as firms do not take into account the negative externality of debris generated by their activities in space. Given that the negative externality affects all firms, there is under-investment in debris mitigation technologies. Adilov et al. (2018) construct an explicit physical model, formalizing the interactions between satellites and debris fragments over an infinite horizon. Under perfect competition, they characterize the equilibrium behavior of firms, assuming that they have adaptative expectations and launch satellites as long as their expected marginal revenue is larger than their expected marginal cost. They use a net present value approach to determine that the threshold level of debris for economic viability is lower than the "Kessler syndrome" level identified by Kessler and Cour-Palais (1978) and find an initial positive relationship between launches and debris, to replace satellites destroyed, the relationship being negative after a threshold level of debris is reached. Macauley (2015) presented different technological strategies to mitigate debris generation and/or collision risk, including manoeuvring capability, grave-yarding capability and shielding, and argues that a launch tax system, combined with various ex ante and ex post rebates, would incentivize investment in these strategies.

Adapting the methodology used in fisheries economics (Gordon 1954; Schaefer 1957), Rouillon (2020) focuses on the long-run stationary state of the orbital environment. He shows that, under given conditions, the curve representing the long-term fleet of active satellites as a function of the launch rate has an inverted-U shape. The analysis confirms that firms launch too many satellites under perfect competition. The main lesson to be drawn from this initial literature is that the current legal framework, authorizing de facto open access to the Earth's orbit, is leading the space industry to over-exploit it. Putting this in perspective with the Kessler syndrome, we are inclined to worry about the risk of the space industry clogging up the Earth's orbit to the point of triggering a chain reaction that will eventually render it unusable. However, Adilov et al. (2018) and Bongers and Torres (2023) come to a reassuring conclusion, by showing that there exists a threshold level of debris for economic viability which is lower than the "Kessler syndrome" level identified by Kessler and Cour-Palais (1978). Bongers and Torres (2023) developed a standard dynamic investment model to study the relationship between satellites and debris. The calibrated model is used to estimate the maximum number of satellites in orbit to prevent further debris increases.

The papers mentioned above draw some useful intuitions from theoretical models. However, this first step calls for a follow-up, involving the simulation of calibrated models, to predict the evolution of the orbital environment and inform decision-making. First simulations were provided by Klima at al. (2016, 2018), Adilov et al. (2020), Rao et al. (2020), and Bongers and Torres (2023). Adilov et al. (2020) expand and calibrate their model in Adilov et al. (2018). In their baseline simulation, the debris stock increases at an increasing rate throughout the century, faster than projected by NASA's reference model. The authors argue that the discrepancy is mainly due to endogenizing the behavior of the space industry by taking its incentives into account. Rao et al. (2020) use an applied model, calibrated on physical and economic data from 1957 to 2015, to simulate the trajectories of open-access and optimal launches until 2040. Under open-access, they project a trajectory of satellite launches increasing from around 50 satellites per year in 2020, to around 80 satellites per year in 2040, a rate that is around twice as fast as the social optimum. The result would be a further accumulation of debris in orbit over the period, when it would be socially optimal to drastically reduce the debris stock. These results can be used to also show that the cost of inaction would be considerable, since the net present value of the satellite industry would be around 600 billion dollars under open access, compared with around 3,000 billion dollars under an optimal policy.

Bongers and Torres (2023) calculate the equilibrium on a competitive market where firms launch and operate satellites to maximize their discounted profits, taking the risk of collision as exogenously given. They compare two scenarios, depending on whether there is a risk of satellite destruction by debris or not. In the steady state, they simulate that the risk of collision induces firms to reduce the number of launches by 3.7 percent and the number of satellites in orbit by 4.5 percent. Moreover, the fleet of satellites remains far below the Kessler threshold, which they estimate equal to around 72,000 satellites for all low earth orbit. The model simulations are often broken down into several exogenous scenarios, to provide a sensitivity analysis. Adilov et al. (2020) diversify their scenarios, considering varying degrees of compliance with debris mitigation guidelines, a launch tax and various levels of debris removal effort. For their part, Bongers and Torres (2023) propose a sensitivity analysis to take account of two technological developments currently underway, namely lower launch costs and satellite miniaturization.

Managerial and technological solutions considered to manage the problem caused by debris in orbit can be classified into three categories, i.e., emissions mitigation, adaptation and active debris removal (ADR) policies. Emissions mitigation refers to actions aimed at reducing the creation of debris, such as limiting accidental break-ups and improving the ability to spot debris and maneuverer satellites during operational lifetime, and de-orbiting of end-of-life satellites. Adaptation consists of designing more robust satellites to reduce both own-damage risk and debris generation in collisions. Finally, ADR policies represent an ex-post intervention and imply cleaning the space by using some technology to reduce the number of orbital debris.

The Inter-Agency Space Debris Coordination Committee (IADC), and the Committee on the Peaceful Uses of Outer Space of the United Nations have established a set of space debris mitigation guidelines to be followed by the governmental space agencies in the design of spacecraft and launch systems to reduce or eliminate generation of debris. Importantly, these recommendations are non-binding and current compliance rates so far are not sufficient to prevent further growth in space debris population (ESA, 2023, annual report). Rao et al. (2020) warns against the risk of relying exclusively on managerial and technological solutions. Even if the mitigation guidelines were fully followed and a dynamic debris removal market were organized, it should be borne in mind that these solutions treat the symptoms but not the cause of the problem. Admittedly, they will slow down the accumulation of debris and delay the moment when the risk of collision will warn the space industry. However, by increasing the profitability of the satellite services sector, they will also encourage the launch of additional satellites. Moreover, this rebound effect is likely to be rapid and powerful, given that the space industry has entered the New Space era, characterized by a high capacity for responsiveness and innovation (Weinzierl, 2018; Adilov et al., 2023).

Kessler and Cour-Palais (1978) called for the implementation of different methods to reduces orbit debris, including improved engineering designs to reduces the frequency of satellite break ups from structural failure and explosions in space, and by reducing the number of non-operational satellites. Macauley (2015) enumerates different technological strategies to mitigate debris generation and/or collision risk. First, graveyarding capability to move dead spacecraft to a high-altitude orbit (above 30,000 km) or to low altitude (below 500 km) for re-entry in the atmosphere. Second, manoeuvring capability to change orbit in case of risk of collision. The possibility of collisions has been avoided by collision-avoidance manoeuvres. reports that more than 100 collision-avoidance manoeuvres to avoid a hit by debris are executed every year by satellite operators. Finally, a third possible strategy is satellite's shielding. This implies a reinforcement of satellites with stronger material that reduces both destruction risk and new debris generation of collisions, although this is only practical in the case of debris of small size. Guyot and Rouillon (2021) investigate how changes in the design of satellites affect debris dynamics proposing a model in which, in addition to the rate of launches, satellite operators make design choices concerning the durability of their satellites. Guyot and Rouillon (2023) extend previous analysis and construct a model where satellite operators make choices about the design and launch of satellites, while in-orbit servicing firms supply efforts to remove space debris. The incentive scheme that they imagine to implement an optimal is a combination of an ad valorem tax, a launch tax, and a market for removal effort certificates.

Active debris mitigation proposals are limited to the study of the development of alternative technologies for debris removal. Active debris removal (ADR) policies are difficult to the implemented by several factors. First, no individual agent (nations or private firms) has incentives to pursue this type of policies as there is no property rights on the space (except spacecraft ownership). Second, any ADR technology as a dual-use, as they can be used to eliminate orbital debris or be used against enemy spacecraft as a space weapon. However, these technologies are expensive, face difficulties for practical implementation as no scheme for how to distribute the cost among operator is available, and finally, to the dual-use nature of debris removal technologies, as they can be considered as anti-satellite weapon systems. However, no active coordinated policy has been implemented to reduces the generation of new debris or to remove existing debris from orbit. Weeden (2011) and Mark and Kamath (2019) survey active debris removal methods currently in development (e.g., laser, ion beam, tether, sail, satellite, foam) to clean up polluted orbital regions. Mark and Kamath (2019) note that these technologies are at best still in the experimental stage and will require a substantial research effort before they reach maturity. Moreover, even when operational, current international treaties applicable to space is likely to hinder the emergence of a market for orbital debris removal (Weeden, 2011; Salter, 2016). On the one hand, objects in orbit come under the jurisdiction of the launching countries. Secondly, any damage caused during a mission in orbit is the responsibility of the country of origin in the event of fault.

A growing literature has studied the role of environmental policies in the space. Space pollution can be controlled by using some type of policy instruments such as taxes or cap-and-control to mitigate emissions or by ex-post interventions by the use of ADR policies. Klima et al. (2016) used a game theory approach whereby spacefaring agencies have the option of implementing costly active debris removal interventions that benefit all spacefaring agents or waiting for other agents carry out the work. Grzelka and Wagner (2019) developed a model containing property rights and instruments to incentivize ex ante increases in satellite quality, and collective or individual debris take-back interventions. Béal, Deschamps and Moulin (2020) compared the non-cooperative Nash equilibrium with a tax on launches to finance debris mitigation, with the welfare optimal traffic under a centralized tax. They found that, under a centralized tax, the traffic is increased, and the debris mitigation cost is reduced compared with the non-cooperative scenario. Rao et al. (2020) developed a model with infinity-lived satellites to study the implications of Pigouvian taxation consisting of an international orbital-use fee. Adilov et al. (2020) simulated the quantity of orbital debris under different policies, including a launch tax, voluntary debris mitigation, and active debris removal policies. This project aims to contribute to the literature by developing an alternative model based on the standard neoclassical dynamic investment model to explore the consequences of orbital debris for the optimal number of satellites and launches, and the implications of launch cost declines and an increasing number of satellites per launch. In a decentralized environment, and given the characteristics of the outer-space market, in which there is no supervisory authority, the negative externality arising from debris is not internalized by operating firms.

To avoid potential rebound effects, the managerial and technological solutions described above should therefore be complemented by economic instruments. Classically, the aim is to correct the externality by confronting economic agents with the true cost of their choice. Since fragments are the very cause of the externality, a Pigouvian tax on debris emitted, reflecting the associated discounted value of future damage, would appear at first sight to be the most effective instrument (Guyot and Rouillon, 2023). However, both in practice and in theory, implementing a Pigouvian tax could be challenging, because the fragments generated after a satellite destruction are not detectable by radar below a size of 10 cm and can potentially be responsible for cascading collisions. What is more, since a collision involves two objects, liability is necessarily joint. Several second-best economic instruments have been discussed in the literature. The most common one is the launch tax (Adilov et al., 2014; Béal et al., 2020; Guyot and Rouillon, 2023; Macauley, 2023; Rouillon, 2023). In simple settings, where firms confine themselves to choosing the rate at which they launch satellites, a launch tax proves to be effective, in the sense that it allows to internalize the externality induced by the fragmentation of satellites.

However, as Rao et al. (2020) rightly assert, this property is likely to fail in more realistic models, where firms also make choices about satellite design and mitigation actions. For instance, a launch tax provides no incentive to design satellites with a longer operational lifetime and/or with de-orbiting capability at the end of their operational lifetime. Yet, the risk of collision is proportional to the total length of time the satellites remain in orbit. In this respect, Rao et al. (2020) argue that an orbital tax would do better than a launch tax. Thus, under the constraint that it is not feasible to levy a Pigouvian tax on the debris generated by a collision, implementing an optimal outcome will require a combination of instruments to guide all the choices influencing the risk of collision and the amount of debris generated. Adilov et al. (2023b) suggest a system of interest-bearing deorbiting performance bonds to incentivize firms to deorbit their expended satellites. Bernhard, Deschamps and Zaccour (2023), and Guyot and Rouillon (2023) formalize a competitive game à la Cournot. Bernhard et al. (2023) solve a dynamic game for evaluating the implication of satellite constellations, in which duopolistic firms choose their number of launches per period, in a context where the debris stock is kept constant by the exogenous action of a space agency in charge of debris removal.

Following the tradition of Integrated Assessment Models (IAM) in the environmental literature, a natural step in considering the implications of orbital debris and optimal policy is the development of integrated macroeconomy-space models. Some initial attempts have been done in the literature as Rao and Letizia (2022), Rao et al. (2023), and Nozawa et al. (2023). Rao and Letizia (2022) combine an econometric model of space activity with a debris environment model based in a Particle-in-a-Box (PIB) model. Another example of IAM for orbital debris is the OPUS (Orbital Debris Propagators Unified with Economic Systems) model developed by Rao et al. (2023). The model incorporates an astrodynamic propagator to assess the state of objects in orbit combined with a simple economic model to determine launch activity. The model is used for evaluating policy proposals for managing orbital congestion. Nozawa et al. (2023) use a neoclassical growth model to study economic activity and the damage produced by orbital pollution and estimate that debris will cause negative damage of approximately 1.95% of global GDP in 200 years if no debris is remediated at all.

6. Industry in the space

Nowadays, the most important commercial activity stablished in the outer space is that of satellites providing services to Earth' consumers. Communications, broadcasting, remote sensing, weather observation, geo positioning, etc., are high-value services by satellites that report several benefits for consumers and firms in the Earth. New constellations of satellites are expanding the industry, by allowing access to internet from any location in the Earth. But this is just the tip of the iceberg, and a large variety of other commercial activities will dawn in the next years, producing new goods and services not only for consumers in the Earth, but also for space-based consumers, including in-orbit manufacturing, R&D activities, in-orbit services as refuelling, up-grading, maintenance, and repair, asteroid mining, energy power generation, tourism, etc.

Apart from the development of new services to Earth consumers, as autonomous vehicles transportation control, drone control, etc., a space-indigenous industry is expected to be dawn, not immediately, but in the future. We define in-orbit manufacturing as the industry to be developed in the outer space to produce goods to the supplied to consumers in the outer space. The most advanced program laying the principles of this industry is the in-space manufacturing (ISM) project at NASA (Prater et al. 2018). Another industrial branch will be the spacecraft manufacturing sector, and possibly, the main industry in the space will be the construction of spacecraft. Initial development of this industry will need material from the Earth, but it could be the case to be transformed in an input autonomous from the Earth industry. Launches from the Earth will change from spacecraft manufactured in the Earth to material needed for manufacturing the spacecraft in the space. In the future, this means that the space industry based in the earth will translate to the space, eliminating the need of launching spacecraft from the Earth. Repairs, upgrading hardware and maintenance services will also change the industry in the next years, affecting the design and lifespan of satellites. Indeed, refuelling is an important service with important implications not only for the lifespan of satellites, but also due to its role as a passive debris mitigation activity. Refuelling activities will eliminate the problem of derelict satellites abandoned in orbit, reducing the negative externalities produced by debris and congestion of precious orbit slots.

Guyot and Rouillon (2023) considers a model with in-orbit servicing firms that supply efforts to remove orbital debris. They focus on the stationary state of the orbital environment, reducing themselves to a static game. Oligopolistic firms make choices about the design and launch of their satellites, and their debris removal effort. In this framework, the satellite industry may have an interest in cleaning up the orbital environment. However, the size of the operating satellite fleet and the loss of social surplus increases with the number of actors in the market.

Apart from in-orbit industry we can identify a few areas that will change the current configuration of services produced by satellites to Earth customers. These areas are natural resources, energy and tourism. Natural resources economics is another branch to be extended to the space. Indeed, extraction of natural resources is one of the most promising avenues for economic activity in the outer space. Asteroid mining is an industry expected to be developed in the next future and with important economic implications for these markets in the Earth (Sonter, 1997; Ross, 2001; Hein et al., 2020). Space mining will increase the supply of critical metal in the Earth which are limited. Weitzman (1999) estimates the world loss in consumption from the finiteness of Earth's resources in about 1 percent compared to a trajectory where mineral results are infinity.

A number of already established private companies (most of them based on Luxemburg) are investing in asteroid mining technologies which will transform the supply of natural material, eliminating depletion of these non-renewable material in the Earth, removing the restriction imposed by the Hotelling non-renewable price equation (Hotelling, 1937). This would require the development of new models, introducing two important elements: cost of exploration, that presumably will be high in this mining industry, and the existence of an environment where resources are non-exhaustible, where investing in exploration will increase the reserves of resources, contrary to standard models of natural resources restricted to the Earth. Several questions emerge as property rights of the mine or asteroid. Some studies have been done in this issue. Sommariva et al. (2020) estimate the net present value of moon mining, and how is affected by the private-public partnership. Dahl et al. (2020) use a model of firm entry to study the consequences on the terrestrial mineral market of asteroid mining.

Fleming et al. (2023) study how space mining could contribute to economic growth. For that, they extend the neoclassical growth model with space mining, breaking down the limitations of mineral resources in the Earth. They find that space mining could lead to continued growth of metal use in the Earth, while limiting environmental costs. Fleming et al. (2023) use a growth model to study the implication of asteroid mining. They assume that the economy only produces one metal, which can be extracted in the Earth or in the space with no limits. Mineral extraction in the Earth produces emissions. They find that transition from mining on Earth to space not only allow for continued growth of metal use, but also limits environmental damage on Earth.

Asteroid mining is not the only natural resource that can be obtain from the space. Supply of energy produced in the space to the Earth is another issue. Indeed, energy generation from the Sun is another promising sector currency under evaluation to be developed in the space. This is the so-called space-based solar power (SBSP) energy systems, consisting in spacecraft that collect solar energy, convert it into electric power, and then transmit the power to a final consumer (Macauley and Davis, 2002). Macauley and Davis (2002) estimated the economic implications of space solar power as a source of electricity for space-based activities, whereas Wood and Gilbert (2022) focus on the implications of supply energy from SBSP to the Earth.

Other industries, such as space tourism, have a potential yet to be calibrated (Cohen and Spector, 2019; Spector and Higham, 2019). Space tourism implies the use of the space and spacecraft for leisure and recreational purposes. Several private companies already offer these services, both orbital and suborbital space travels, such as Blue Origin, Virgin Galactic, Space Adventures, Axiom Spaces and SpaceX. See Zhang and Wang (2020) of a revision of a growing space tourism literature which have studied aspects as motivation and preferences, potential demand estimation, prices and revenues evolution, types of space tourism, etc. A common wisdom is that space tourism industry is in its infancy as the commercial passengers flights industry were one Century ago. Finally, space burial is another service consisting in small capsules that are burn up in the re-entry to the atmosphere, suborbital, in the moon, or that are sent further into space. Commercial activity of space burials started in 1997 by the US company Celestis. However, the first space burial was done by NASA in 1992 with the remains of the creator of Start Trek. Space burials are not only restricted to remains of human but also pets. The first burial in the deep space was conducted by NASA on 2006 with the remains of the American astronomer Clyde Tombaugh.

7. Outer space and defence economics

Military and civilian satellites provide strategic advantages for security, national defence, and warfare, making military considerations a pivotal aspect of human activities in outer space. The militarization of space began with the advent of space exploration itself, primarily through the adaptation of ballistic missiles to deploy spacecraft into orbit. The military utilization of outer space naturally follows from the technological benefits that satellites offer in terms of warfare and security. The deployment of space capabilities for defence purposes not only enhances the military capacity of spacefaring nations but also supports arms control treaties by improving verification and monitoring. Moreover, military applications in space are crucial for modern warfare, influencing technology, tactics, and military doctrine among leading powers. Initially, space exploration was heavily influenced by military goals, including the military origins of launch systems and the growing defence interest in space given its vast potential for military operations. Military communications, meteorological forecasting for operations, geographic positioning of combat units, control and guidance of precision weapon systems, surveillance, and intelligence gathering are all indispensable for contemporary defence and warfare strategies. These factors have led to an increased militarization of outer space, with a significant number of military satellites located in Medium Earth Orbit (MEO).

However, the militarization of outer space encompasses not only passive, non-weaponized military equipment but also includes the development of anti-satellite (ASAT) weapon systems by some spacefaring nations. Koplow (2009) noted that the U.S.

began developing ASAT weapons just weeks after the Soviet Union launched Sputnik I. Crucially, the traditional distinction between militarization and weaponization blurs in outer space, where any object capable of manoeuvring at high velocities can potentially be used as a weapon (White, 2017). This erosion of distinction has detrimental effects on other human activities in outer space. The militarization of space could significantly hinder the development of in-space industries and the implementation of policies aimed at reducing orbital pollution through active debris removal. While the mere presence of more operational satellites—contributing to the congestion of near-Earth orbit—might seem like a direct negative impact of militarization, the strategic importance of these assets for national defence and warfare makes them targets for adversaries, thus potentially transforming space into a battlefield where also civil spacecraft would be military targets.

Several international initiatives have surged to limit the weaponization (militarization is accepted with no restriction) of outer space. The United Nations COPUOS (Committee on the Peaceful Uses of Outer Space) was established in 1959 as a basis for international cooperation among the spacefaring nations in the exploration of outer space. The Outer Space Treaty (OST), signed in 1967, states that space must be used for peaceful purposes. However, the OST banned the military use of outer space in a very lax way. In truth, the OST only banned the use of nuclear and mass destruction weapons in outer space (Article IV), leaving any other military activity insufficiently regulated, although the Treaty calls for the peaceful use of space. As indicated by Bourbonniere and Lee (2008), the placement of conventional weapons, including systems with nuclear drives, does not violate the Treaty. After some ASAT tests with nuclear weapons were carried out during the period 1958-1962 by the US and the Soviet Union, the Partial Test Ban Treaty, formally titled The Treaty Banning Nuclear Weapon Tests in the Atmosphere, in Outer Space and Under Water of 1963, banned such tests. More recently, two major spacefaring countries, China and Russia, presented a proposal in the year 2008 to "define and prohibit the proliferation of weapons in space", which was named the PPWT (Treaty on the Prevention of the Placement of Weapons in Outer Space, the Threat or Use of Force against Outer Space Objects). However, this proposed Treaty was rejected by the US, leading to a space arms race and accelerating the development of space weapon systems by China and Russia. More recently, in April 2024, Japan and the US proposed a resolution that reaffirm provisions in the Outer Space Treaty prohibiting the placement of nuclear weapons or other weapons of mass destruction in space, but was rejected by Russia, whereas China abstained.

Numerous international initiatives have emerged to curb the weaponization of outer space, although militarization itself faces fewer restrictions. The United Nations established the Committee on the Peaceful Uses of Outer Space (COPUOS) in 1959 to foster international cooperation among spacefaring nations in space exploration. The Outer Space Treaty (OST), signed in 1967, mandates that space be used for peaceful purposes. However, the treaty only weakly restricts military use of outer space. Specifically, the OST prohibits the placement of nuclear weapons and weapons of mass destruction in outer space (Article IV) but leaves other military activities largely unregulated, despite its general call for peace. As noted by Bourbonniere and Lee (2008), the deployment of conventional weapons, including those powered by nuclear propulsion, does not contravene the treaty. Following nuclear-armed anti-satellite (ASAT) tests conducted by the US and the Soviet Union between 1958 and 1962, the Partial Test Ban Treaty of 1963 was introduced, which prohibited such tests in the atmosphere, outer space, and underwater. In 2008, China and Russia presented a draft for the Treaty on the Prevention of the Placement of Weapons in Outer Space and the Threat or Use of Force against Outer Space Objects (PPWT), aimed at defining and prohibiting the proliferation of space weapons. However, the United States rejected this proposal, intensifying an arms race in space and spurring China and Russia to accelerate their development of space weapon systems. More recently, in April 2024, Japan and the United States put forward a resolution to reaffirm provisions of the Outer Space Treaty against placing nuclear or other weapons of mass destruction in space, but it was rejected by Russia, while China abstained.

From an economic perspective, the military use of outer space has three main implications. First, the militarization and weaponization of space directly affect the population and dynamics of orbital debris. A significant proportion of launches and satellites are military in nature, contributing to the density of objects in orbit and the production of debris. Consequently, military activity in space is a notable source of orbital debris. Additionally, for operational reasons, many military satellites remain in orbit beyond their functional lifespan, transforming into space junk and increasing the risk of collisions with active satellites. Furthermore, a substantial amount of orbital debris has been intentionally created through the testing of direct-ascent (DA) anti-satellite (ASAT) weapons. These tests typically involve destroying a target satellite with a missile or the self-destruction of the weapon itself, generating a significant amount of new orbital debris. A notable incident was the intentional destruction of the Chinese Feng-Yun 1C satellite by a missile in January 2007, which increased the population of trackable space debris—those pieces larger than 10 cm—by 30%, resulting in 3,449 catalogued fragments (OECD, 2020). Up to 2010, ASAT tests accounted for about 41% of orbital debris (Wright, 2011), and this percentage is much higher if the DA-ASAT test conducted by China in 2007 and the most recent test by Russia in 2021 are included.

Second, the development of debris removal vehicles is controversial due to their dual-use potential; they can also function as anti-satellite (ASAT) weapons, posing an obstacle to the implementation of active mitigation policies aimed at reducing orbital pollution (Dobos and Prazak, 2019). Indeed, any technology designed for active debris removal could be repurposed as a weapon, since it has the capability to remove any object from orbit, including adversary satellites.

Third, the emerging in-orbit services industry is similarly threatened by military considerations. Space services such as refuelling, upgrading, maintenance, and repairs of satellites could be compromised. These activities require the use of space vehicles that, given their capabilities, could also be utilized as ASAT weapons. The unique conditions of space mean that practically any spacecraft has the potential to be used as an ASAT weapon.

Phillips and Pohl (2021) explored the issue of orbital debris from a behavioral economics perspective, examining its impact on national defense. They argued that orbital debris poses a significant threat to the security interests of spacefaring nations. Bernat (2019) highlighted the growing strategic importance of satellites and other orbital systems, noting that this has led major spacefaring countries to develop advanced space weapon systems and specialized units for space warfare. Bongers and Torres (2024) analyzed the implications of ASAT tests and space warfare on orbital debris. They employed a straightforward physical-economic model to demonstrate how anti-satellite military tests, especially those using direct-ascent weapons, substantially increase the likelihood of triggering the Kessler syndrome. While the long-term impact of low-altitude anti-satellite tests is mitigated by atmospheric drag, high-altitude direct-ascent anti-satellite tests pose a persistent threat to human activities in space. Their paper also simulates the long-term effects of a hypothetical space war, assuming the destruction of 250 satellites by the US and China. Such a conflict would have severe consequences. The interruption of high-value satellite services would disrupt normal life, severely impairing military operational capacities. Without long-term communication, reconnaissance, GPS for drones and guided bombs, and even weather information, the effectiveness of modern forces would be drastically reduced. Moreover, the potential for conflict extends into outer space, which could become a future battlefield. In such a scenario, military satellites, critical for enemy military operations, would become prime targets. Similarly, one's own military satellites would also be at risk. In the event of a conflict between spacefaring nations, this would generate a substantial amount of debris, posing an additional threat to any remaining operational satellites.

8. Satellites and economic data

Another field of economics related to outer space involves the application of data collected by Earth observation satellites to measure economic activity, economic growth, and other types of economic analysis, such as policy evaluation. Earth observation satellites can measure a wide variety of both natural and human-made phenomena on Earth, including economic activity. These satellites have sensors that detect artificial light, which can be converted into data and used as a proxy for variables such as population and economic activity geographical concentration. Croft (1978) was the first to demonstrate how nighttime light information from weather observation satellites could be used to study population density, economic activity, oilfield gas flaring, and agricultural fires. Since Croft’s seminal work, data from Earth observation satellites have been widely used for empirical economic analysis, given some advantages of this type of data although they are not free of problems. Donalson and Storeygard (2016) provide an excellent early review of the literature, while a more recent outstanding review is offered by Gibson, Olivia, and Boe-Gibson (2020), though the focus of these works differs.

As Donalson and Storeygard (2013) highlight, spatial remote sensing data aids the study of the economy in three key aspects: i) access to information that is difficult to obtain by other means; ii) high spatial resolution; and iii) broad geographic coverage. Indeed, satellite nighttime lights can be used for producing-subnational economic statistics, even for small rural areas, and for less-developed countries characterized by inaccurate and/or lack of statistics. Another advantage is the frequency. Satellite nighttime light data can be obtained in a dairy basin, a frequency much higher than traditional statistics. Gibson et al. (2020) list possible applications of nighttime data, including ex post evaluation of public projects, political manipulation, regional favoritism, and evaluation of country sanctions, even if the available information was not initially designed for economic analysis.

The first generation of studies used data from the Earth Observing System (EOS) program by the US, which is a space-based environmental data collection project. The data comes from the U.S. Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS), available publicly from 1973 and, more comprehensively, from 1992 when the digital archive was made public (Gibson et al., 2020). The original idea was to use night light data as a proxy for economic activity. An early study by Elvidge et al. (1997) used nighttime data from DMSP-OLS to estimate light emissions in 21 countries and examine their relationship with population, economic activity, and electric power consumption. They found that the area lit is highly correlated with population, gross domestic product (GDP), and electric power consumption, even in highly heterogeneous countries. Sutton and Costanza (2002) estimated that the correlation between light energy and GDP is 0.86 for U.S. states and extended the analysis to estimate economic activity and non-marketed activity at a 1km^2 resolution globally. Ebener et al. (2005) used nighttime lights imagery to study the distribution of income per capita at a regional sub-national level. Doll, Muller, and Morley (2006) utilized DMSP-OLS data to estimate GDP for 11 European Union countries and the United States with a resolution of 5km^2, finding that the correlation of light radiance with GDP at a regional or state level is above 0.9, except for France. Burchfield et al. (2006) used satellite images to study U.S. urban development and sprawling in metropolitan areas, creating a grid of 8.7 billion 30x30 meter cells for the U.S.

Following previous initial contributions Henderson, Storeygard and Weild (2011, 2012) developed a statistical framework for augmenting official income growth statistics with satellite data. Henderson et al. (2011) identify two important drawback of using nighttime lights from space to measure income: i) the relationship between economic activity and lights is not constant across time and space; and ii) true light is imperfectly measured by satellites. Henderson et al. (2011, 2012) measure GDP growth for cities and subnational regions in Sub Sahara Africa. Gallimberti (2020) develops some statistical procedures to extract new predictive information from the lights data for forecasting GDP growth across a global sample of countries and find that i) night lights data can be used to improve the accuracy of model-based forecasts and ii) the relationship between lights and economic activity is very different across countries.

From 2012 onward, more accurate data on night lights are available from the Soumi National Polar-orbiting Partnership (NPP) satellite. This is the so-called VIIRS-DNB data, obtained from the Joint Polar-orbiting Satellite System (JPSS), the Visible and Infrared Imaging Suite (VIIRS) Day Night Band (DNB). Chen and Nordhaus (2019) compare estimates from using DMSP-OLS versus VIIRS-DNB data. They apply the two data set to both US states and metropolitan statistical areas (MSAs), and find that that both the DMSP-OLS and the VIIRS-DNB nighttime lights are more useful in predicting cross-sectional GDP than predicting time-series GDP data, and are better for prediction for MSA GDP than for state GDP, which is interpreted as that lights are more closely related to urban sectors than rural sectors.

Apart from measuring economic activity, another application of those data is related to the detection of measurement errors in national and regional accounts. Nighttime lights data has fueled the debate about reliability of GDP data for low- and medium-income countries. Sutton, Elvidge and Ghosh (2007) use satellite data for the US, China, India and Turkey, and show that nighttime imaginary data are highly accurate to estimate GDP. Chen and Nordhaus (2011) compare luminosity data with GDP at country level and show that both measures coincide for countries with high-quality statistical systems. The use of satellite nighttime lights to assess the quality of economic statistics has also been dealt by Pinkovskiy and Sala-i-Martin (2016) who show that measurement errors in DMSP-OLS nighttime light data are unrelated to the measurement errors in national accounts or household surveys. Pinkovskiy and Sala-i-Martin (2020) use nighttime lights to compare Penn World Table (PWT) and World Development Indicators (WDT) data in predicting GDP, concluding that GDP series based on unadjusted domestic growth rates are better than series based on purchasing power parity adjustment. Pinkovskiy and Sala-i-Martin (2020) using nighttime data find that Chinese growth in 2015 has been higher than that reported by official statistics. By contrast, Hu and Yao (2022) estimate that the elasticity of nighttime lights to GDP is about 1.3 (using DMSP-OLS data) and find that GDP growth of China and India has been overestimated in official statistics based on an optimal combination of nighttime lights and national accounts data.

Apart from previous studies, other dimensions remain to be explored. Space data can transform deeply availability of economic data in two important dimensions: frequency of economic data and spatial data. First, changes in economic activity growth could be detected instantaneously thanks to continuous remote sensing. Economic activity could be measured in a daily basin or even can be used to increases the frequency of national accounts. Second, this data can be used for business cycle forecasting and early detection of turning points, improving macroeconomic forecasting and rapid updating of forecasting. Any change in the cycle can be detected just in-time. On the other hand, availability of production data for any level of aggregation, from cities to regions. This could be used for measurement errors of traditional statistics by comparing and the check data reliability for other less-quality data, as shown by Chen and Nordhaus (2011). Finally, another utility of satellite Earth's observation is the detection of the informal economy (Sutton et al., 2007; Henderson et al., 2012). Informal economy is not measured in official statistics, and nighttime light data can be used to complement estimations of the black economy. The applications in economics extend further. National, regional and other low spatial unit accounts, and economic growth are not the only areas in which space data will have a significant role. Environmental, energy and transportation economics, are other fields where data generated from the space can contribute greatly.

Existing data from the space are generated by Earth-observation satellites not specifically designed to collect data to be used in economics. One step ahead could be the definition of data-collection characteristic for economic purposes and even the design of specific satellites for measuring economic activity and other economic purposes as policy evaluation. This opens the door to the collaboration between economists and space national agencies for the design, construction, calibration, and launch of a specific satellite or the inclusion of specific sensors in satellites for collecting economic data from the Earth from the Space. This would revolutionize availability of economic data through the possibility, for instance, of generating high-frequency data on production growth, activity reallocation, real-time measurement of the effects of shocks and policies, and leading indicators of economic forecasting. Such advances will significantly enhance data availability for empirical economists, enabling measurement of income distribution and economic growth at any temporal frequency and spatial unit, and improving the reliability for measuring economic activity in other area with poor statistics.

9. Concluding remarks

Humankind is just at the beginning of exploring outer space, but significant progress has been made over the past sixty years. The space economy is in its infancy, but alongside its growth, a number of economic issues are emerging due to expanding human activities in space. These issues demand attention from the economic profession. Although space economics is a nascent field, there have been several recent contributions. This review covers most of the initial contributions to this new field. The nature of outer space as an international commons alerts us to potential market failures and the need for regulation. Given the increasing value of outer space, it is expected that more economic studies will emerge in this new and largely unexplored area.

The development of space economics will require adapting existing economic models to the unique physical characteristics of space and its new resource and technological constraints. It may even necessitate the development of new theoretical frameworks to address emerging economic issues as human presence in space increases. An open question is which standard economic analysis tools can be applied to space economics. In principle, space economics will share several issues with well-established economic fields, so tools from these fields could be applied to similar issues observed on Earth. However, the physical characteristics of space will play a role, and new types of Integrated Assessment Models, combining economic and physical variables of space, will be necessary.

In the future, more branches of space economics, connected to other economic branches such as natural resources, environmental economics, transportation, energy, new product industries, R&D, tourism, and defense, are expected to develop. Two important areas are likely to attract more attention from economists. The first concerns the regulatory framework. Commercial activities in outer space will require an international regulatory framework to assign property rights at different altitudes. The second main research area will be the space environment. In a short period, the space environment has become highly polluted with space debris. Investigating optimal environmental policies for space and the most appropriate abatement instruments will require the development of space-economy integrated assessment models in the tradition of the DICE model by Nordhaus (2008).

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