ON EFFICIENT AND FAIR MANAGEMENT OF THE SPACE DEBRIS CONGESTION PROBLEM: A PRELIMINARY THEORETICAL ASSESSMENT ON STEADY STATE

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On efficient and fair management of the space debris congestion problem

*A preliminary theoretical assessment on steady state**

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Abstract

Contemporary societies differ radically from all earlier ones in that they make daily use of space probes, satellites, and space stations. An unwanted side-effect of this development is the continuing production of space debris. Increasing awareness of and concern over this growing problem means the time has come to ensure the sustainable use of space by removing some of the debris. We investigate how to manage this problem in a steady state through the formation of an international institution tasked with preventing the production of new debris and removing some existing debris *efficiently* and *equitably*. This preliminary study concludes that this is feasible although it should be emphasized that, under asymmetric information, our model identifies discordance between efficiency and fairness, and consequently an ambiguous effect as concerns the occurrence of the Kessler syndrome.

Keywords:
Outer space, space debris, non-profit-organization, incentives, efficiency, fairness, asymetric information, Kessler's syndrome

JEL codes:
D63, D82, H21, K33, K34, Q50

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"As space debris poses a problem for the near-Earth environment on a global scale, only globally supported solutions can be the answer"
Inter-Agency Space Debris Coordination Committee (IADC) [2025, p. 4]

1 Introduction

Outer space fascinates and inspires humankind. It is the stuff of dreams even though there is still no universally accepted defnition of where it actually begins. While the consensus seems to be to take the Karman line as separating the Earth's atmosphere from outer space, quite where that line lies between 70 and 100 km above the Earth's surface varies with commentators, countries, and organizations.[1] What is beyond dispute, though, is that outer space was inaccessible for most of human history. Only since the mid-20th century, with the launch of the first Sputnik 1 satellite on October 4, 1957, the first spacewalk on March 18, 1965 (Voskhod 2), the first man on the Moon on July 21, 1969 (Apollo 11), and the completion of the first space station on April 19, 1971 (Saliout 1), has space become a new horizon for humankind. This was the beginning of the space age.

Today, as part of the productive structure, the space economy amounts to between $415 billion according to Bryce Tech [2025] and $613 according to the Space Foundation [2025], with nearly three-quarters of this amount coming from satellite-related industries. However, this figure is extremely simplistic, and current demand for space-related activities is far greater and will be even more so for future generations. Today, no country or individual can forgo the services afforded by space without incurring some cost or loss of opportunity. Even a cursory overview of those services includes scientific, civil, commercial, and military uses and applications. Space is indispensable for scientific knowledge (e.g., the James Webb telescope), telecommunications (e.g., telemedicine, smart cities), observations (e.g., monitoring of water on the Earth's surface with the SWOT satellite, meteorology with the European Copernicus program), and navigation (e.g., satellite geo-positioning systems GPS, GLONASS, Galileo, Beidou, IRNSS). Space is also essential for understanding and protecting the biosphere, understood as all the ecosystems present in the lithosphere, hydrosphere, and atmosphere. Of the 55 vari-

[1] While the approach and inspiration stemming from the work of physicist Theodore von Karman remains relevant, there are many debates today, particularly among specialists, as evidenced, for example, by McDowell [2018]. We will use here the *Fédération Aéronautique Internationale* convention and define the Karman line at 100 km above the Earth's surface

ables identified by the GCOS (Global Climate Observing System) for climate monitoring, 32 can only be observed from space. Finally, the military has a long and lasting interest in space, in domains including intelligence gathering, telecommunications and military operations (e.g., future air combat systems), as well as issues of sovereignty and the protection of strategic infrastructure.

These applications concern all countries and all sectors of activity. They are largely the outcome of a process that has been ongoing in the space industry for several decades, commonly referred to as New Space (or Space 2.0) resulting from a combination of regulatory, technological, and commercial breakthroughs. Until the 1990s, space programs were essentially centralized, kept separate from other components of production structures, and were governmental or inter-governmental. Then, from the 2000s onwards, the U.S. executive branch authorized the commercial use of high-resolution satellite images, the dissemination of higher-precision GPS to the general public, and the evolution of NASA's structure from a hierarchical model (e.g., the Apollo program) to a commercial network model, with public-private contracts and service contracts (e.g., Commercial Resupply Services and Commercial Orbital Transportation Services). Technological innovations included the miniaturization of components and satellites (cubesats), more efficient propulsion systems, the advent of 3D printing, lower manufacturing costs[2], the linking of space applications with information and communication technologies, and reusable launchers. All these changes, some of which can be attributed to the arrival of new players from outside the space industry, are radically reshaping the space industry (i.e., launchers and satellites) and its applications. As an illustration, launching a satellite with SpaceX today costs less than 8% of what it did before 2000. These developments lead Weinzierl et al. [2022] to argue that every company, whatever its field, must now rethink its space strategy and to claim that we are at the dawn of a new era, with the transition from exclusively space-for-earth applications (which remain the only real ones to date), to space-for-space applications (Weinzierl and Sarang [2021]).

UNOOSA (United Nations Office for Outer Space Affairs) maintains an official register of all objects sent into space. Since 1962, it has recorded 21,405 objects sent into space[3], and the company Look Up Space now es-

[2]Elon Musk has decided, for example, to build the cylinders of his launchers using the welded sheet metal technology used by grain silo manufacturers, whereas previously they were machined.

[3]https://www.unoosa.org/oosa/osoindex/search-ng.jspx?lf_id=(September 2025)

timates the number of active satellites at over 10,000 (most of the 2/3 belonging to Starlink)[4]. By way of comparison, there were a total of around 1,000 active satellites in 2010 and 5,500 active satellites in 2023. Of the current total, 9/10 are in Low Earth Orbit (LEO) (i.e., between 100 and 2,000 km altitude), and there are only around 300 satellites in geostationary orbit (around 36,000 km altitude). Moreover, space remains a very challenging environment, with certain specific physical characteristics (e.g., gravity gradient, slosh, solar radiation pressure, magnetic hysteresis and energy dissipation, universal attraction between objects).

Unfortunately, beyond all their benefits for humans, space activities are increasingly generating pollution and congestion. This includes pollution of the hydrosphere (e.g., when an object falls into the seas), pollution of the atmosphere (e.g., hydrazine combustion), light pollution, and radio interference. Although all of these forms of pollution require serious consideration, the present paper must ignore them and concentrate instead on the issue of space clutter caused by space debris.[5]

The history of space debris is intertwined with the history of the space age given that humans began leaving debris in outer space right from the launching of *Sputnik 1* in 1957. The main sources of space debris are launchers, failed or abandoned satellites, explosions in orbit due to unspent fuel and undisconnected batteries, wear and tear of materials, collisions between objects in space, and the willful destruction of satellites.[6] There are three main types of debris: smaller than 1 cm, larger than 1 cm and smaller than 10 cm, and larger than 10 cm. As the experts remind us, in terms of kinetic energy, an object with a radius of 1 mm in space is equivalent to a bowling ball launched at 100 km/hr; an object of 1 cm corresponds to a saloon car travelling at 130 km/hr, and an object of 10 cm is equivalent to the explosion of a 240-kg charge of TNT. A satellite can therefore be destroyed by debris 1 cm in diameter and severely damaged by debris just 1 mm in size. All debris larger than 10 cm is individually recorded and constantly tracked by USSPACECOM and NASA (USA) (see graph below) and now by EU STT (EU), with civil and military radars. The current solution is to avoid debris by maneuvering, which is difficult and costly. For debris between 0.1 cm and

[4] https://fr.linkedin.com/posts/look-up-space_nous-y-sommes-le-cap-des-10000-satellites-activity-7208203368928870400-0Y9o (June 2024)

[5] We use the term "clutter" rather than "pollution" here, as there is currently no known ecosystem in space.

[6] We refer here to anti-satellite firings, with which four countries (the USA, China, Russia, and India) have already experimented.

1 cm, which cannot be catalogued, the solution is to take this into account in the architecture of the objects and to provide shielding. On the other hand, there is no solution for debris between 1 and 10 cm, as it is too large to be stopped by shielding and too small to be detected and tracked. Before falling back to Earth, debris will remain in space for 2,000 years if at an altitude of 1,200 km, 1,000 years if at 1,000 km, and 200 years if at 800 km. The risk of totally losing a space station, such as the ISS (located between 350 and 400 km), over fifteen years, due to debris, is of the order of 5%, and it is generally estimated that the probability of losing a satellite, over its lifetime, due to debris, is currently of the order of 8% (the European Space Agency ESA estimates that by 2038 the risk of collision will be of the order of 20%). Currently, the ESA [2024, p. 26] estimates that 26,000 pieces of debris are larger than 10 cm, 900,000 are smaller than 10 cm and larger than 1 cm, and 128 million are smaller than 1 cm and larger than 1 mm. More than 80 collision alerts a year are issued by CNES and the ISS maneuvers almost monthly.

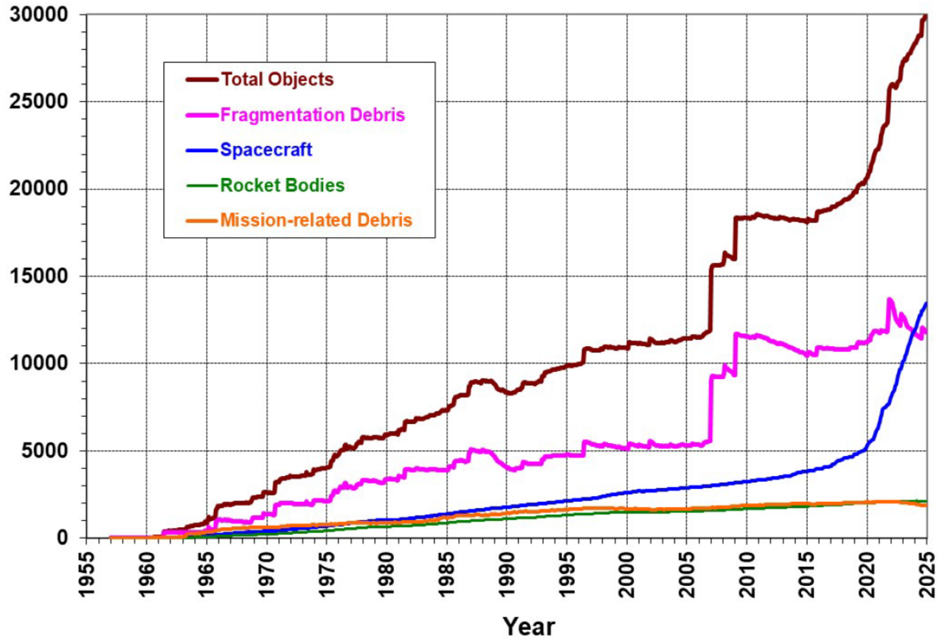


Figure 1: Evolution of the number of pieces of debris catalogued in Earth orbit (Liou [2025])

To the best of our knowledge, the seminal works in economics concerning outer space are those by Snow [1975], O'Neill [1977], and Sandler and Schulze [1981]. Today, Weinzierl's overview [2018] serves as the benchmark, not least because it offers a comprehensive presentation, taking into account the advances, opportunities, and risks associated with New Space. However, it is only in the last 10 years or so that a small number of economists, following Adilov et al. [2015] and Macauley [2015], have begun to take a specific interest in the market failures leading to the increase in space debris, and in ways of solving the problems debris poses in the more or less long term. Today, this growing body of literature comprises, in the broadest sense, around 30 articles. It is therefore obviously out of place to give an exhaustive presentation here, and we refer in particular to the articles cited recently in the contributions by Bongers and Torres [2023] and Guyot et al. [2023] for an overview.

The aim of the present paper is to contribute to the current debate on how to manage *efficiently* and *equitably*, over the long term, the production of new space debris and the removal of existing debris or debris that may still be created (e.g., by a company that fails to comply with the rules, or a company that goes bankrupt and leaves no financial assets). To this end, we hypothesize that an international institution (i.e., a non-profit organization) could be set up to ensure the sustainable use of outer space with the authority to set a mandatory minimum standard for the quality of space missions deploying satellites and the capacity to tax all heterogenous companies deploying satellites in space. We then compare, focusing on the steady state, the situation where the international agency has perfect information about the characteristics of firms in terms of their technological compliance with the minimum standard (i.e., symmetric information) and the situation where the international agency has only imperfect knowledge of these characteristics in relation to the minimum standard (i.e., asymmetric information).

Our proposition 1 demonstrates that, in a situation of symmetric information, there is both efficiency (i.e., the number of satellites launched maximizes gross profit) and fairness (i.e., all firms make the same profit after taxes)[7]. Our proposition 2 shows that in a situation of asymmetric information, the international institution can only implement a policy that is less equitable than the one it would implement in a situation of symmetric information, due to the incentives it must provide to encourage companies to reveal their true characteristics. This implies that firms' profits after tax no longer satisfy the fairness requirement, with the result that fewer satellites will be launched. With regard to the Kessler syndrome[8], the main conclusion of this model

[7] See Section 5 below for a discussion on fairness.

[8] In the late 1970s, Don Kessler produced an analysis indicating that beyond a certain level of debris, the total amount of space junk will continue to increase, rendering Low Earth Orbits physically unusable for several generations. This effect arises because collisions between debris generate other debris and lead to further collisions, in a chain

(propositions 3 and 4) is that the effect of information asymmetry on the quantitative side is either positive if the tax collected to remove debris is the same, or ambiguous if it is lower, because fewer satellites are deployed. Qualitatively, this effect is negative: the quality of objects in space declines. Thus, even assuming the best possible coordination (i.e., a single international institution), the occurrence of the Kessler syndrome may be reduced or increased due to information asymmetry.

The paper is organized as follows. Section 2 presents our framework, outlining assumptions and the maximization program of an international non-profit organization (NPO) in charge of both reducing the production of new space debris and cleaning up existing debris. Section 3 examines the NPO's optimal management in the symmetric information case as in the asymmetric information case. Section 4 analyses the effects of the asymmetric information case in our model concerning the occurrence of the Kessler syndrome. Section 5 discusses our assumptions and findings. Section 6 concludes the paper by presenting the avenues we believe it would be worth exploring in future research.

2 General framework

Background Consider an international non-profit organization (NPO) tasked with sustainably removing debris from space (at least the larger debris). To do this, the NPO first sets a minimum quality standard that future satellite missions must satisfy. Second, it announces a tax schedule such that a firm must pay the tax T if it launches q satellites[9].

The NPO faces a mass 1 of a continuum of firms deploying satellites. A firm is more or less efficient at adapting its technology to the new standards. This efficiency or type is a private information denoted by β. When deploying q satellites, the firm's profit is $\pi(\beta, q)$. We assume that this profit is a concave single-peaked function in q that increases with β, even at the margin[10]: $\pi_\beta(\beta, q) > 0, \pi_{\beta q}(\beta, q) > 0$.

There is asymmetric information between the NPO and firms (i.e., the

reaction (Kessler and Cour-Palais [1978]). The 2013 movie Gravity, directed by Alfonso Cuarón, illustrates this phenomenon.

[9]We assume that the satellites are of the same size for simplicity's sake, but this model could be used for each satellite size if you have families of satellites.

[10]We use here subscripts to denote partial derivative.

NPO is unable to observe a firm's type). It only has prior beliefs over type summarized by a density probability function $f(.) > 0$ on $B = [\beta_0, \beta_1]$. The cumulative distribution function is denoted $F(.)$.

Guesnerie and Laffont [1984] state there is no loss of generality in focusing on a direct revelation mechanism, $\langle T(\tilde{\beta}), q(\tilde{\beta})\rangle|_{\tilde{\beta}\in B}$. This mechanism specifies the tax paid $T(\tilde{\beta})$ in exchange for the number of satellites that can be deployed $q(\tilde{\beta})$ if a firm reports to have a type $\tilde{\beta}$.

Thus, the firm's profit after tax is:

$$\Pi(\beta, \tilde{\beta}) = \pi(\beta, q(\tilde{\beta})) - T(\tilde{\beta}). \tag{1}$$

The NPO's objective function is:

$$W = \int_B G(\Pi(\beta)) f(\beta) d\beta, \tag{2}$$

with $\Pi(\beta) \equiv \Pi(\beta, \beta)$ and where G is the NPO's evaluation of the firm's profit after tax. We assume that the marginal value of Π is positive and decreasing. In other words, the NPO seeks to promote business, which implies $G'(\Pi(\beta)) > 0$, and fairness by favoring firms whose profitability is low because of the new standards, i.e. $G''(\Pi(\beta)) < 0$.

We denote by K the cost of cleaning up space. This is an exogenous fixed cost corresponding to the amount needed to finance removal of space debris, given the techniques available. NPO operating costs are taken to be fixed (because of steady state), and therefore only shift our results. Without loss of generality, we can therefore consider them to be 0.

In the following, we will assume that the virtual[11] profit, $\pi(\beta, q) - \pi_\beta(\beta, q)\frac{1-F(\beta)}{f(\beta)}$, is a concave single-peaked function in q. As usual in incentives theory (see Laffont and Martimort [2002]), this assumption ensures that the profit, $\pi(\beta, q)$, less the cost of the incentives due to asymmetric information, $\pi_\beta(\beta, q)\frac{1-F(\beta)}{f(\beta)}$, keeps the properties of the profit.

[11] The term is coined by Myerson [1979].

The NPO's problem The NPO faces three types of constraint:

- *the budget constraint*: cleaning the space requires to recover the amount K, i.e. $\int_B T(\beta)f(\beta)d\beta \geq K$ or, using (1):

$$\int_B (\pi(\beta, q(\beta)) - \Pi(\beta))f(\beta)d\beta \geq K; \tag{3}$$

- *the incentive constraints*: a firm has no interest to lie on its efficiency, i.e. $\forall \beta, \tilde{\beta} \in B, \Pi(\beta) \geq \Pi(\beta, \tilde{\beta})$, or:[12]

$$\begin{cases} \dot{\Pi}(\beta) = \pi_\beta(\beta, q(\beta)); \\ \dot{q}(\beta) \geq 0. \end{cases} \tag{4}$$

- *the individual rationality constraints*: a firm cannot end up with a negative payoff, i.e. $\forall \beta \in B, \Pi(\beta) \geq 0$ or:[13]

$$\Pi(\beta_0) \geq 0. \tag{5}$$

The problem that the NPO must resolve is thus to $\max_{\langle q(\beta), \Pi(\beta) \rangle}$ the objective function (equation 2) subject to its three constraints (equations (3), (4), and (5)).

3 The NPO's optimal management

3.1 The symmetric information case

The benchmark considers that information is symmetric: it is assumed that the NPO can observe the firm's efficiency. Hence, the incentive constraints (4) do not matter. It follows that the problem to resolve is to maximize the objective function (equation (2)) subject to the budget constraint (equation(3)) and the participation constraints in its initial form $\forall \beta \in B, \Pi(\beta) \geq 0$. The benchmark policy is given in the following proposition.

[12] The incentive constraints are necessarily satisfied if $\beta = \arg\max_{\tilde{\beta}} \pi(\beta, q(\tilde{\beta})) - T(\tilde{\beta})$. So, we must have 1) $\pi_q(\beta, q(\beta))\dot{q}(\beta) - \dot{T}(\beta) = 0$, and 2) $\pi_{qq}(\beta, q(\beta))\dot{q}(\beta)^2 + \pi_q(\beta, q(\beta))\ddot{q}(\beta) - \ddot{T}(\beta) \leq 0$. Differentiating the first equation, the second is equivalent to $\dot{q}(\beta) \geq 0$ since $\pi_{\beta q}(\beta, q(\beta)) > 0$. Moreover, using the first equation, differentiating $\Pi(\beta)$ implies $\dot{\Pi}(\beta) = \pi_\beta(\beta, q(\beta))$. Finally, since $\pi_{\beta q}(\beta, q) > 0$, these conditions are also sufficient.

[13] Since $\dot{\Pi}(\beta) > 0$, (5) is sufficient.

Proposition 1 *Let λ be the shadow price of the budget constraint. The benchmark for managing debris removal entails:*

$$G'(\Pi^b) - \lambda^b = 0, \tag{6}$$

$$\pi_q(\beta, q^b(\beta)) = 0. \tag{7}$$

This proposition calls for comment. First, notice that the positive shadow price of the budget constraint, $\lambda = G' > 0$, implies that the budget constraint is binding: collect more tax than necessary to clean space has no interest for the NPO because it would unnecessarily decrease the firms' profit and so decrease its own objective function.

Second, since its valuation of profit, G, is strictly increasing, the NPO seeks to increase profit after tax as much as possible. But, this goal is constrained by the fact that this reduces the amount of tax collected (see (3)). It becomes optimal to increase a firm's after-tax profit until its marginal valuation, G', equals its marginal cost, 1, weighted by the shadow price of the budget constraint, λ (equation (6)).

Third, the overall number of satellites deployed, i.e. $Q^b = \int_B q^b(\beta) f(\beta) d\beta$, is efficient since for each β the number deployed is such that its marginal profit, $\pi_q(\beta, q)$, is equal to zero (equation (7)).

Fourth, we observe that λ does not depend on the type β. So neither does the firm's after-tax profit, meaning that all types make the same amount of profit. This result reflects the two objectives of the NPO: to promote business through a fair policy so that the after-tax profit, $\Pi = \pi(\beta, q) - T$, is equal whatever the type.

Finally, combining (3) and the elements of the proposition 1, the level of profit is given by:

$$\Pi^b = \int_B \pi(\beta, q^b(\beta)) f(\beta) d\beta - K. \tag{8}$$

3.2 The asymmetric information case

To begin, recall that λ is the shadow price of the budget constraint. The following proposition states the optimal policy.[14]

[14] For simplicity, we ignore the constraint $\dot{q}(\beta) \geq 0$ by considering that the solution will imply $\dot{q}(\beta) > 0$. The major consequence is that we ignore partial pooling policies but this does not affect our main results.

Proposition 2 *Managing debris removal under asymetric information entails:*

$$\Pi^*(\beta) = \Pi^*(\beta_0) + \int_{\beta_0}^{\beta} \pi_\beta(\varepsilon, q^*(\varepsilon))d\varepsilon, \tag{9}$$

$$\Pi^*(\beta_0) \geq 0, \tag{10}$$

$$\pi_q(\beta, q^*(\beta)) + \frac{\pi_{\beta q}(\beta, q^*(\beta))\left(\int_\beta^{\beta_1}\left(G'(\Pi^*(\varepsilon)) - \lambda^*\right)f(\varepsilon)d\varepsilon\right)}{f(\beta)\lambda^*} = 0, \tag{11}$$

$$\lambda^* = \int_B G'(\Pi^*(\beta))f(\beta)d\beta. \tag{12}$$

This proposition calls for a number of comments.

The consequences of asymmetric information. Because of asymmetric information, the NPO is no longer able to observe firms' efficiency. It is well known in incentives theory (see Laffont and Martimort [2002]) that the constant benchmark after-tax profit, Π^b, is not incentive-compatible: a firm with a given type has an incentive to mimic lowest types so as to pay less tax, thereby increasing its net profit after tax. To avoid these incentives, the NPO must call for an after-tax profit that is increasing in type so as to force firms to reveal their true type. This is given by (9). This entails two consequences: 1) firms receive a level of after-tax profit that differs with their efficiency, 2) each firm receives at least $\Pi(\beta_0)$ in after-tax profit which, using (10), may be zero.

This enables us to appraise the implication of asymmetric information on fairness in the following corollary.

Corollary 1 *Due to asymmetric information, optimal NPO management results in less fairness.*

The consequences of the lack of fairness. The lack of fairness due to the necessity of incentives when information is asymmetric comes at a cost for the NPO. This cost is evaluated by the shadow price associated to the first part of the incentives constraint (4). It is captured by the the biggest parentheses of the numerator in the second term of the LHS of (11).

Indeed, when the NPO leaves 1$ of after-tax profit to firms of efficiency β, the NPO must leave this dollar to all firms with higher types, and so increase their after-tax profit, otherwise incentives are not ensured and they would mimic β. This has two contrasting effects. On the one hand, this dollar contributes to increasing the objective function by $G'(\Pi(\beta))$ for all higher types. This is a benefit for the NPO, represented by $\int_{\beta}^{\beta_1} G'(\Pi(\varepsilon))f(\varepsilon)d\varepsilon$. On the other hand, this same dollar represents a cost for the NPO because it makes it harder to collect taxes to cover the cost of cleaning up space K (see (3)). It is measured by $\int_{\beta}^{\beta_1} f(\varepsilon)d\varepsilon$, i.e., the proportion of the firms $1 - F(\beta)$ that benefit from this dollar rent, weighted by the shadow price of the budget constraint λ.

What is the dominant effect? Except for the highest type β_1 where the two terms are null and the lowest type β_0 where the two terms offset one another (make use of (12)), it depends on the sign of these parentheses because $\pi_{\beta q}(\beta, q(\beta)) > 0$. Applying the mean-value theorem, it can be shown that this sign is given by $\forall \beta \in (\beta_0, \beta_1)$:[15]

$$G'(\Pi(\overline{\beta}(\beta)) - G'(\Pi(\overline{\beta}(\beta_0)) < 0, \tag{13}$$

where $\overline{\beta}(\beta)$ belongs to $[\beta, \beta_1)$. This is strictly negative. Thus, the costly effect of the incentives dominates the beneficial effect for each $\beta \in (\beta_0, \beta_1)$.

Now let us observe why the shadow price of the informational rent is null at the bounds: at β_1, because this type cannot be mimicked by higher ones; at β_0 because the objective function always benefit from a non-negative after-tax profit for this type.

Combining (7), (11), and (13), we observe that the lack of fairness forces the NPO to distort quantities. Again using (13) and the concavity of π in q, these distortions are downward. This entails the following trade-off: the NPO reduces the slope of $\dot{\Pi}(\beta)$ since $\pi_{\beta q}(\beta, q) > 0$, and thus limits the lack of fairness which is, it will be recalled, costly for it. We can state the next corollary.

Corollary 2 *To contain the lack of fairness, optimal management by the NPO entails downward distortions of quantities below the benchmark level.*

The consequences of both lack of fairness and distortions. These have the following two consequences on the NPO's trade-offs. First, since we just have proved that (13) cannot be null or positive, by (11) we cannot have

$$\pi_q(\beta, q(\beta)) = 0, \forall \beta \in (\beta_0, \beta_1),$$

[15]Indeed, we have $\int_{\beta}^{\beta_1} G'(\Pi^*(\varepsilon))f(\varepsilon)d\varepsilon = G'(\Pi(\overline{\beta}(\beta)))(1 - F(\beta))$ and, making use of (12), $\lambda(1 - F(\beta)) = G'(\Pi(\overline{\beta}(\beta_0)))(1 - F(\beta))$. Simplifying by $(1 - F(\beta))$ leads to (13) since $\Pi'(\beta) > 0$, $\beta_0 < \beta$, and $G'' < 0$.

which implies, denoting $Q^* = \int_B q^*(\beta)f(\beta)d\beta$,

$$Q^* < Q^b. \tag{14}$$

Second, after integration by parts of $\int_\beta \Pi(\beta)f(\beta)d\beta$, the budget constraint can be rewritten

$$\Pi(\beta_0) = \int_B \left(\pi(\beta, q(\beta)) - \pi_\beta(\beta, q(\beta))\frac{1-F(\beta)}{f(\beta)}\right) f(\beta)d\beta - K. \tag{15}$$

The immediate implication is, by (8), that[16]

$$\Pi^*(\beta_0) < \Pi^b. \tag{16}$$

To conclude, we can summarize the consequences of the preceding two points on business promotion in a new corollary.

Corollary 3 *Due to the lack of fairness and distortions, optimal management by the NPO promotes less business since*

- *the overall number of satellites deployed is not efficient by* (14)*,*
- *the minimal amount of profit obtained by all types is lower by* (16)*.*

4 Effects on the occurrence of the Kessler syndrome

We analyze the role of the information on the risk of Kessler syndrome occurrence (KSO).

We already know that the overall number of satellites deployed are such that $Q^* < Q^b$.

Moreover, recall that it is impossible for the NPO to clean up space at a cost that would imply that firms earn negative profits after tax as this would violate their individual rationality. Thus, we can determine the maximum cost of cleaning up space by making the participation constraints binding[17] in (8) and (15). We obtain $\bar{K}^b = \int_B \pi(\beta, q^b(\beta))f(\beta)d\beta$ under symmetric

[16] Indeed, $\forall \beta \in (\beta_0, \beta_1), \pi(\beta, q^*(\beta)) - \pi_\beta(\beta, q^*(\beta))\frac{1-F(\beta)}{f(\beta)} < \pi(\beta, q^*(\beta)) < \pi(\beta, q^b(\beta))$.

[17] That is, $\Pi^b = 0$ with symmetric information, $\Pi^*(\beta_0) = 0$ with asymmetric information.

information, and $\bar{K}^* = \int_B \left(\pi(\beta, q^*(\beta)) - \pi_\beta(\beta, q^*(\beta))\frac{1-F(\beta)}{f(\beta)}\right) f(\beta)d\beta$ under asymmetric information. But, we necessarily have[18]

$$\bar{K}^b > \bar{K}^*. \tag{17}$$

We are now equipped to analyze the risk of KSO first in its quantitative, then in its qualitative aspects.

Proposition 3 (Quantitative aspect) *If $K \leq \bar{K}^*$, the asymmetry of information reduces the risk of reaching the KSO threshold.*
If $K > \bar{K}^*$, asymmetric information has an ambiguous effect on such a risk.

In the first case, the amount of debris removed is the same whatever the nature of information. Thus the amount of debris remaining in the space is also the same. In parallel, asymmetry of information involves fewer satellites being deployed overall, which implies that the amount of potential new debris declines too. Therefore, asymmetric information reduces the risk of reaching the KSO threshold.

In the second case, what changes is that less debris is removed under asymmetric information. It follows that more of the existing debris remains in space. Clearly, this countervails the beneficial effect due to the overall quantity. Asymmetric information thus has an ambiguous effect on the risk of reaching the KSO threshold.

Proposition 4 (Qualitative aspects) *Let $K > \bar{K}^*$. The asymmetry of information increases the risk of reaching the KSO threshold.*

To simplify the analysis, let us consider the case where the number of objects in the space is the same whatever the nature of information. We have already proved that asymmetric information leads:

- to fewer satellites being deployed,
- to less debris being cleared up if $K > \bar{K}^*$,

than symmetry of information. Thus, under asymmetric information, space contains more old objects and fewer new satellites. The quality of space is greater with symmetric information. This implies that asymmetric information increases the risk of reaching the KSO threshold.

[18] Use footnote 16 again.

5 Discussion

A discussion of some of the above points is obviously necessary to better grasp their scope, but also to better understand their level of crudeness. Beyond the formal aspects, we would like to organize this discussion around three questions: Is there a problem? If so, what institution(s) would have the authority and means to solve it in the long term? What principle(s) should this (these) institution(s) apply to ensure efficiency and fairness?

Space debris problem There are and will be no problems with space debris in four alternative situations: 1/ if we stop using space, 2/ if we take no interest in the future, 3/ if it is always possible to avoid a collision with debris, or 4/ if collisions have no effect. The first two situations are absurd, whereas the other two are science fiction for the time being. And while the natural risks associated with cometary and asteroidal material (meteoroids) were assessed very early on (e.g., Davidson and Winslow [1961]), it is only really since Kessler's work that the question of artificial debris has come in for serious consideration. Today, almost 50 years later, as the problem of space debris continues to grow and threaten the future, it has to be said that: 1/ there is no legal definition of what constitutes space debris, 2/ there are no mandatory rules prohibiting the production of debris in LEO, 3/ there are no mandatory rules requiring the removal of debris in LEO, 4/ there is no legal procedure for the removal of debris, 5/ there are no mandatory rules governing the construction and design of satellites, and 6/ there is no space "highway code".

Does this mean that nothing has been done throughout this period? Fortunately no, but all the initiatives and efforts made by a great many specialists, some institutions (e.g., IADC, COPUOS, ISO), firms, as well as the main space agencies, have only led to the establishment of a number of non-binding agreements. When it comes to space debris, there is only soft law, and the best estimates suggest that only 60% of signatories to these types of agreements actually abide by them.

In other words, we physically have growing problems with space debris, and we have political, legal, and economic problems in solving them, particularly in Low Earth Orbits (i.e., between 100 and 2000 km).

Institution(s) to solve the problem in long term We therefore need to start thinking today about the institution(s) that will have sufficient power and resources to resolve these problems in the long term. In the absence of a world government, these questions are of course part of the classic literature on collective action, with the particularity (as with climate change) that the relevant geographical scale corresponds to the world as a whole. Furthermore, as with climate change, these questions involve interactions among tiers of stakeholders (firms, countries, groups of countries), adding to the problems of sovereignty.

A priori, four solutions seem conceivable.

Firstly, as Olson [1965] pointed out, it is sometimes possible for a single agent to have such vested interests that it finds it advantageous to provide the public good itself, in this case the removal of all space debris. After all, the U.S. surveillance network USSTRATCOM has long been the only one to track debris larger than 10 cm and disseminate the information to other nations in space. It would be possible, then, to imagine that tomorrow the USA (or China) might take it upon itself to remove all space debris, given the economic interests involved. We do not believe in this solution, because the cost could be very high, but above all because it seems to us to be unacceptable to all other nations, if only because of the dual aspect of active debris removal technologies, which also have a potential military capability. Moreover, in the best-case scenario, this solution could only be transitory, since it is hard to imagine that, in the long term, a single state would continue to remove the debris that firms from all the other states would continue to leave.

Secondly, we could imagine the removal of space debris being the responsibility of two (or more) coalitions of countries, along the lines of those currently being formed with the Artemis accords, and the IRLS (International Lunar Research Station), concerning the civil and commercial exploration and the peaceful use of the Moon. This would naturally lighten the financial burden of space debris removal (since it would be shared), but at the same time it would raise the notorious free-rider issue. As Finus [2024] points out, in this type of problem there is the question of which countries would agree to be members (and therefore which countries would not participate but still benefit from the work done by others), and also, within the members of a coalition, the question of whether states would stand by their commitments, since they can leave the coalition at any time. In addition, having two (or more) separate coalitions would necessarily raise problems of coordination between them.

Thirdly, extending the previous perspective, we could imagine the removal of space debris being the subject of a single international agreement involving all countries. Although the vast economic literature on international agreements, which dates at least as far back as Barrett's work (e.g., Barrett [1994]), is generally pessimistic about the success of such agreements, and current agreements on climate change unfortunately still appear insufficient to really meet the IPCC's recommendations, we have to note that academic research is making progress. In this respect, the article by Kornek and Edenhofer [2020] proposing a transfer scheme along the lines of mechanism design theory in a two-stage coalition formation game, amended by Finus [2024], offers the hope of obtaining a "super-model" (to use Finus's expression) enabling, even in the context of asymmetric nations, the two aspects of free-riding to be resolved.

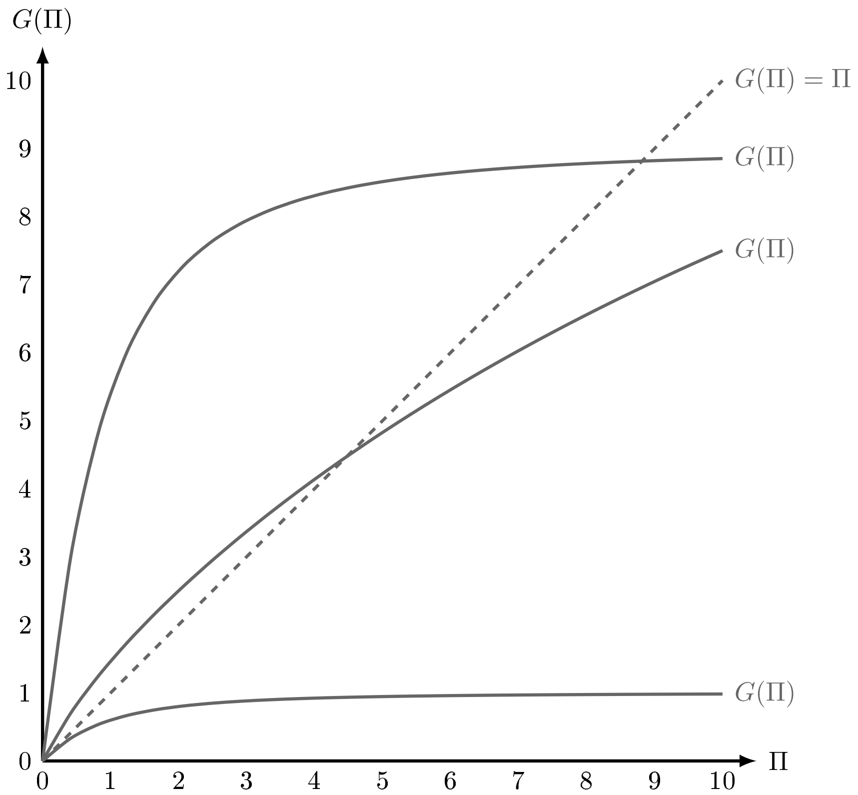
Fourthly and lastly, we could imagine an international institution that would be tasked by all the countries on the planet with resolving the issue of space debris.

In this article, we have clearly placed ourselves, by hypothesis, within the framework of the latter solution, totally disregarding the factors that would enable such a solution to be achieved. Apart from the point that other authors have already proposed this approach to solving the question of space debris (e.g., Béal et al. [2020], Bernhard et al. [2023]), we have retained this hypothesis (which is the most favorable case) because we wanted to focus our study on the articulation between the principles of efficiency and fairness in the steady state in a situation of asymmetric information. This is clearly a milestone in the analysis of this question, which could serve as a benchmark for further work. We would also like to point out that the supranational authority approach has already been analytically considered in other contexts (in the macroprudential field, e.g., Steiner [2014], and in the field of climate change, e.g., Barnes et al. [2008], Pichler and Sorger [2018]). Finally, what seems perfectly idealistic today, especially given current international relations, could become realistic if certain physical limits are exceeded, opening a window of opportunity for such major changes to the current state.

For the time being, we believe that the United Nations (UN) could be given the responsibilities and powers of the international institution we envisage (i.e., the NPO), for at least four reasons. First, the UN already exists, so there is no need to create a new international organization. Second, the UN is one of the most representative international organizations in the world (193 states are currently members). Third, given the dual nature of space (civil and military), entrusting the UN with these new responsibilities would be the best way to preserve peace. Finally, it should be remembered that the UN already has a long history with outer space (notably through the five international treaties that form the backbone of space law) and that it has two key agencies in this field: the UN Office for Outer Space Affairs (UNOOSA) and the International Telecommunication Union (ITU).

Efficiency and fairness While the question of the efficiency of space debris removal within the framework of a model inspired by the literature on optimal taxation does not seem to pose any major difficulties (it is a question of finding the funds needed to carry out this active debris removal), the same cannot be said of its articulation with the idea that this tax must also be fair. Indeed, the moral habits and standards of justice that structure a given state are not self-evident, as the existence of great diversity in this area proves. Moreover, as Konow [2003] points out, conceptions of what is fair vary with history and context even within one and the same state. As such, we fully agree with Lando's [1997, p. 582] conclusion that: "[...] it seems impossible to escape *ad hoc* specifications of fairness norms".

To come up with our proposal on the subject (i.e., $G''(\Pi(\beta)) < 0$), we started from the fact that, in the stationary state, given the advent of New Space, firms would be the main agents deploying satellites in space; and from the rejection of two solutions. The first would have been to make all firms pay the same amount (egalitarian sharing), which seemed unfair in view of the financial asymmetries between them. The second would have been to make firms pay only according to the number of satellites they deploy (if necessary, by penalizing those who deploy large numbers of satellites ever more heavily), which seemed to us potentially unfair given that a company sending out one satellite of "poor quality" (just up to standard) would have been taxed less than a company sending out two satellites of very "good quality" (well above the standard). We have therefore opted for an approach in the spirit of the Human Development Index, which uses the logarithm of income per capita (not GDP per capita) to reflect the decreasing importance of income. This is, of course, a debatable choice, but we would like to emphasize that the choice of a concave function does not completely limit the existence of political choices, since we also need to define the slope at the origin and the behavior at infinity to fully characterize it. The graph below illustrates this point by proposing three possible forms among all those that the function $G(\Pi)$ could take:



6 Concluding remarks

Although less discussed than other issues, space debris is one of the world's most pressing problems. The first attempts to remove space debris are planed for 2026. Numerous technical proposals exist, and this market is beginning to emerge with the creation of companies specializing in the field (e.g., Astroscale, ClearSpace). It now requires the efforts of the entire international community, starting with the leading space powers, and most certainly institutional and legal innovations.

Our contribution offers a first clue as to how it might be possible, in the long term, to reduce the production of new space debris and finance the removal of existing space debris. Unfortunately, it also points out that with imperfect information there is a trade-off between the objective of efficiency and the objective of fairness, in the sense that we have provisionally given to the latter.

Clearly, this is a preliminary study, and we do not claim to have any definitive conclusions, let alone to be in a position to secure the agreement of all countries to such a framework. However, in view of our current knowledge of the space debris situation and the prospects for it, we are convinced that it is necessary to begin, without delay, to make proposals to ensure the fair and sustainable use of space.

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A Proof of Proposition 1

Let $V(\beta) = \int_{\beta_0}^{\beta} (\pi(\varepsilon, q(\varepsilon)) - \Pi(\varepsilon)) f(\varepsilon) d\varepsilon$. The constraint (3) can be reformulated as $\dot{V}(\beta) = \big(\pi(\beta, q(\beta)) - \Pi(\beta)\big) f(\beta)$ with $V(\beta_0) = 0$ and $V(\beta_1) \geq K$. So the problem becomes an optimal control one where $q(\beta)$ and $\Pi(\beta) \geq 0$ are controls and $V(\beta)$ is a state variable. The Hamiltonian is:

$$H(\beta) = G(\Pi(\beta)) f(\beta) + \lambda(\beta)\big(\pi(\beta, q(\beta)) - \Pi(\beta)\big) f(\beta) \tag{18}$$

with $\lambda(\beta)$ is the co-state variable.

Necessary (and sufficient) conditions are:

$$H_q = \lambda(\beta)\pi_q(\beta, q(\beta)) f(\beta) = 0 \tag{19}$$
$$H_\Pi = (G'(\Pi(\beta)) - \lambda(\beta)) f(\beta) \leq 0 \tag{20}$$
$$\Pi(\beta) H_\Pi = 0 \tag{21}$$
$$\dot{\lambda}(\beta) = -H_V = 0. \tag{22}$$

Transversality conditions are:

$$V(\beta_0) \text{ no condition}; \lambda(\beta_1) \geq 0, \lambda(\beta_1)\big(V(\beta_1) - K\big) = 0. \tag{23}$$

Equation (19) implies $\pi_q(\beta, q(\beta)) = 0$. By (22), we have $\lambda(\beta) = \lambda$ and by (23) $\lambda \geq 0$. So,

- either $\lambda = 0$. From (20), we must have $G'(\Pi(\beta)) \leq 0$ which is not possible.
- or $\lambda > 0$. So, using (20), in this case $G'(\Pi(\beta)) = \lambda > 0 \Rightarrow V(\beta_1) = K$ by (23).

B Proof of Proposition 2

With incomplete information, $\Pi(\beta)$ becomes a state variable. The Hamiltonian is:

$$\mathcal{H}(\beta) = G(\Pi(\beta)) f(\beta) + \lambda(\beta)\big(\pi(\beta, q(\beta)) - \Pi(\beta)\big) f(\beta) + \mu(\beta)\pi_\beta(\beta, q(\beta))$$

where $\mu(\beta)$ is the co-state variable associated with $\Pi(\beta)$.

Necessary equations are:

$$\mathcal{H}_q(\beta) = \lambda(\beta)\pi_q(\beta, q(\beta))f(\beta) + \mu(\beta)\pi_{\beta q}(\beta, q(\beta)) = 0 \tag{24}$$

$$\dot{\lambda}(\beta) = -\mathcal{H}_V = 0 \tag{25}$$

$$\dot{\mu}(\beta) = -\mathcal{H}_\Pi = -G'(\Pi(\beta)) + \lambda(\beta)f(\beta) \tag{26}$$

Transversality conditions are:

$$V(\beta_0) \text{ no condition}; \lambda(\beta_1) \geq 0, \lambda(\beta_1)\big(V(\beta_1) - K\big) = 0. \tag{27}$$

$$\mu(\beta_0) \leq 0, \mu(\beta_0)\Pi(\beta_0) = 0, \mu(\beta_1) = 0. \tag{28}$$

From (25), λ is a constant. Therefore, using (24), the quantity is:

$$\pi_q(\beta, q(\beta)) + \pi_{\beta q}(\beta, q(\beta))\frac{\mu(\beta)}{\lambda f(\beta)} = 0. \tag{29}$$

Moreover, combining (26) and (28), we get:

$$\mu(\beta) = \int_\beta^{\beta_1} G'(\Pi(\varepsilon))f(\varepsilon)d\varepsilon - \lambda(1 - F(\beta)). \tag{30}$$

Then

$$\mu(\beta_0) = \int_{\beta_0}^{\beta_1} G'(\Pi(\beta))f(\beta)d\beta - \lambda$$

$$\Leftrightarrow \lambda = \int_{\beta_0}^{\beta_1} G'(\Pi(\beta))f(\beta)d\beta - \mu(\beta_0). \tag{31}$$

Now let us prove that

$$\mu(\beta_0) = 0. \tag{32}$$

Assume that it is not the case, so $\mu(\beta_0) < 0$ by (28). This has two implications:

- λ is increased by (31), which reflects the fact that K is increased, i.e. the budget constraint is more difficult to satisfy,
- $\Pi(\beta_0) = 0$ by (28), so that the budget constraint (15) can be rewritten as

$$K = \int_B \left(\pi(\beta, q(\beta)) - \pi_\beta(\beta, q(\beta))\frac{1 - F(\beta)}{f(\beta)}\right) f(\beta)d\beta. \tag{33}$$

By assumption, it follows that the only way to satisfy this constraint is to increase q. But, computing the partial derivative of q in (29) with respect to λ (with the help of (30)), implies $\frac{\partial q}{\partial \lambda} < 0$. A contradiction.

Finally:

- inserting (32) into (31) gives (12),
- from (29) and (30), the quantity is given by (11),
- combining (32), (28), and (5) leads to (10),
- integrating (4), we get (9).

The necessary and transversality conditions are also sufficient because first, the objective function G and the budget constraint are respectively strictly concave and linear in Π, and second, the budget constraint is strictly concave in q.

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