Space Debris

A Law and Economics Analysis of the Orbital Commons

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Abstract

In this paper, I examine the problem of *space debris*—detritus from spacecraft launches that remains in orbit—using the tools of economics. The difficulties posed by space debris resemble those typically associated with public goods and common pool resources. Thus it is not surprising that a tragedy of the commons has resulted, in the form of cluttered orbits. However, given the peculiar legal arrangements that characterize space in both domestic and international law, solving this problem is not straightforward. I analyze the difficulties that both private and public actors must overcome if the space debris problem is to be solved. Although proposing a particular solution is beyond the scope of this paper, by addressing the problem from an economic perspective, I clarify the costs that must be considered in order for private and public actors to make informed decisions concerning space debris mitigation and removal.

JEL codes: A1, H1, H4, K1, P14

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1. Introduction

In this paper, I analyze the problems posed by space debris from the perspective of law and economics and of property rights economics. The paper's chief contribution is a more rigorous economic analysis of the problem than currently exists in the literature. NASA (the National Aeronautics and Space Administration) defines *space debris* as "all man-made objects in orbit about the Earth which no longer serve a useful purpose."[1] Examples include upper stages of launch vehicles, solid waste remains emitted by rocket motors, and fragments resulting from collision of existing debris.

Although many pieces of space debris are quite small, their high velocity—between 7 kilometers (km) and 8 km per second in low earth orbit (LEO)—makes collision of debris with spacecraft currently in use, such as communication satellites, an obvious concern. Approximately 300,000 pieces of debris exist of sufficient size to destroy a satellite upon collision. Threats from space debris collision include failure of the satellite-reliant global positioning system, which "could disrupt emergency response services, cripple global banking systems, and interrupt electric power grids," as well as hinder US military capability, which has become increasingly reliant on the system.[2]

The probability of a collision is currently low. Bradley and Wein estimate that the maximum probability in LEO of a collision over the lifetime of a spacecraft remains below one

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[1] National Aeronautics and Space Administration (NASA), *Orbital Debris: Frequently Asked Questions*, NASA ORBITAL DEBRIS PROGRAM OFFICE (Mar. 12, 2012), http://orbitaldebris.jsc.nasa.gov/faqs.html.

[2] Megan Ansdell, *Active Space Debris Removal: Needs, Implications, and Recommendations for Today's Geopolitical Environment,* 21 J. PUB. & INT'L AFF. 7, 8 (2014).

in one thousand, conditional on continued compliance with NASA's deorbiting guidelines.[3] However, the possibility of a future "snowballing" effect, whereby debris collides with other objects, further congesting orbit space, remains a significant concern.[4] Levin and Carroll estimate the average immediate destruction of wealth created by a collision to be approximately $30 million, with an additional $200 million in damages to all currently existing space assets from the debris created by the initial collision.[5] The expected value of destroyed wealth because of collisions, currently small because of the low probability of a collision, can quickly become significant if future collisions result in runaway debris growth.

Given the possibility of high future costs, private and public actors should, for their own benefit, direct attention to the space debris problem now. Global satellite revenue in 2014 totaled $195.2 billion.[6] That stream of economic activity is most threatened by significantly increased concentrations of space debris in orbit. Other activities within the "space economy" ($320 billion in revenue in 2013) that are potentially threatened include human spaceflight and nonorbital spacecraft.[7] Private-sector space activities planned for the more distant future, including space tourism and asteroid mining, will also be affected if access to orbit is complicated by space debris.

Despite the fiscal nature of the problem, economists have thus far paid little attention to space debris. A notable exception is produced by Adilov, Alexander, and Cunningham, who model the problem posed by space debris and consider an optimal corrective tax to deter private

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[3] Andrew M. Bradley & Lawrence M. Wein, *Space Debris: Assessing Risk and Responsibility*, 43 ADVANCES IN SPACE RES. 1372 (2009).
[4] Jer-Chyi Liou & Nicholas L. Johnson, *Risk in Space from Orbiting Debris*, 311 SCI. 340 (2006).
[5] Eugene M. Levin & Joseph A. Carroll, *The Cost of Future Collisions in LEO* 12–15 (Star Technology and Research White Paper, 2012), *available at* http://www.star-tech-inc.com/papers/The_Cost_of_Future_Collisions_in_LEO.pdf.
[6] The Tauri Group, *State of the Satellite Industry*, SATELLITE INDUSTRY ASSOCIATION (Sept. 2014), http://www.sia.org/wp-content/uploads/2014/09/SSIR-September-2014-Update.pdf.
[7] *Id.*

launchers from cluttering orbits.[8] The paper by Adilov et al. is indicative of the paradigm that economics is the science of choice and efficient resource allocation.[9] However, an alternative way of conducting economic analysis is to focus on the institutional environment within which resources are allocated.[10] Because a fuller understanding of the problem requires comparative institutional analysis, I adopt the latter approach here.[11]

In section 2, I present an overview of space debris that helps establish context for the problem. In section 3, I focus on access to orbit and on particular orbits as a public good and a common pool resource, respectively. I also outline the way that law and economics researchers and property rights economists traditionally study those goods and resources. In section 4, I more fully specify the nature of the good (orbit space) in question, with a hypothetical scenario placing the burden for dealing with space debris entirely on the private sector. In section 5, I draw attention to the distinction between mitigating space debris and removing space debris as I focus on the difficulties of removal given current international law. In section 6, I conclude by emphasizing the importance of establishing a publicly announced institutional regime for dealing with space debris problems in the future.

2. Space Debris: A Brief Overview

The first piece of space debris was the rocket body from the launch of Sputnik 1 in 1957. The quantity of space debris objects began growing at a significant rate in June 1961, when the first manufactured space vehicle exploded in orbit, creating nearly 300 pieces of trackable

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[8] Nodir Adilov, Peter J. Alexander & Brendan M. Cunningham, *An Economic Analysis of Earth Orbit Pollution*, 60 ENVTL. & RESOURCE ECON. 81 (2015).
[9] LIONEL ROBBINS, AN ESSAY ON THE NATURE AND SIGNIFICANCE OF ECONOMIC SCIENCE (1932).
[10] *See* James M. Buchanan, *What Should Economists Do?*, 30 S. ECON. J. 213 (1964).
[11] Adilov et al. do acknowledge the importance of the institutional framework, especially the property rights framework, but they focus predominantly on static resource allocations. My analysis also will consider questions of allocation and efficiency, but it will focus more on legal institutions. Adilov et al., *supra* note 8.

debris.[12] Currently, orbit space contains more than 21,000 known pieces of large (>10 centimeters [cm]) space debris, an estimated 300,000 pieces of medium-sized (between 1 cm and 10 cm) debris, and more than 100 million pieces of small debris.[13] Of those, the medium-sized particles pose the greatest risk to existing orbiting spacecraft. Large debris can be tracked, and the location of pieces can be predicted with sufficient accuracy to maneuver spacecraft away from a collision trajectory. Small debris cannot be tracked, but it rarely poses a danger to spacecraft because spacecraft can easily be constructed with sufficient shielding. A subset of the midsized debris poses the largest danger. Those pieces are too small to be tracked but are large enough to destroy a spacecraft in the event of a collision.[14] Figure 1 shows the increase in space debris since 1957.

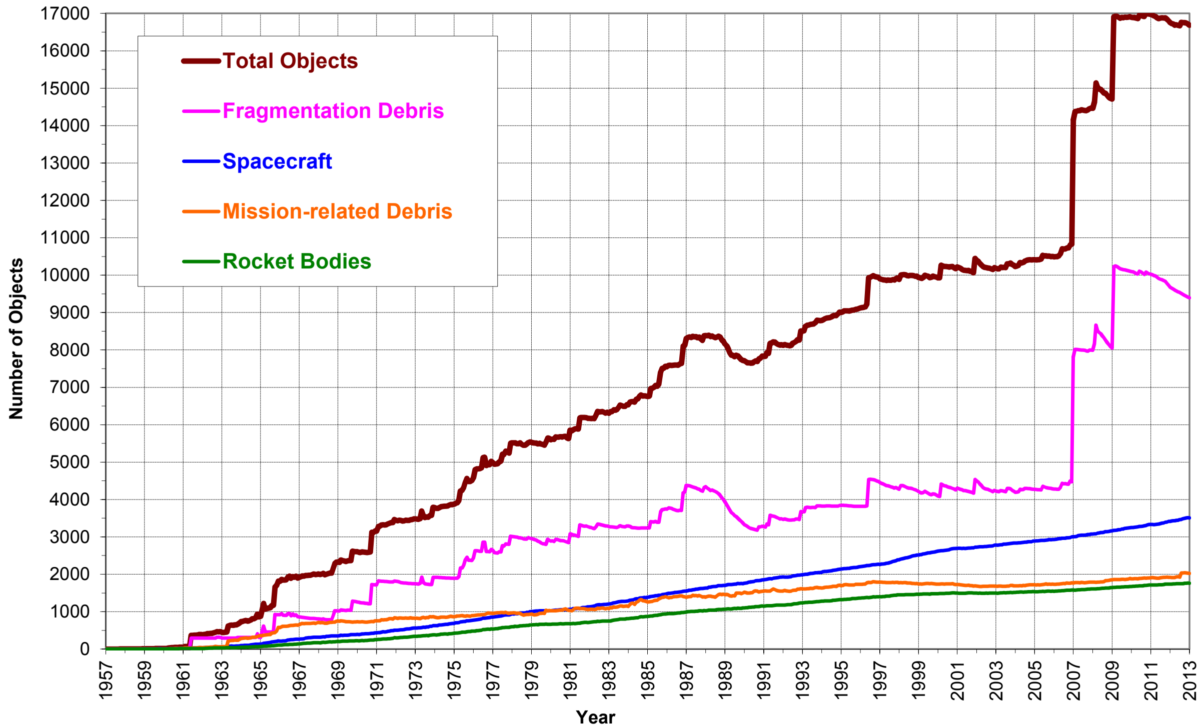
Three spacefaring nations are overwhelmingly responsible for the concentration of debris in earth orbit. China is responsible for approximately 42%, the United States for approximately 27.5%, and Russia for approximately 25.5%.[15] China's disproportionate responsibility for space debris is due to its intentional anti-satellite test conducted on January 11, 2007. In purposefully destroying its Fengyun 1-C satellite, China created at least 150,000 pieces of new debris 1 cm or more in size. That event marked the largest new creation of debris in history up to that point.

Another major space debris–creating event involved Russia. One of Russia's old military satellites collided with a then-operating Iridium Communications satellite on February 10, 2009. Unlike the Chinese case, this collision was unintentional. The collision created more than 200,000 pieces of debris larger than 1 cm. Communications services facilitated by the destroyed

[12] Nicholas L. Johnson, *Orbital Debris: The Growing Threat to Space Operations* 1 (American Astronautical Society Paper No. 10-011, 2010), *available at* http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20100004498.pdf.
[13] National Aeronautics and Space Administration (NASA), *Orbital Debris: Graphics*, NASA ORBITAL DEBRIS PROGRAM OFFICE (October 2, 2012), http://orbitaldebris.jsc.nasa.gov/photogallery/beehives.html#leo.
[14] Ansdell, *supra* note 2.
[15] *Id.* at 10.

satellite were only briefly interrupted. Nonetheless, the incident received significant attention, highlighting the possible problems posed within orbits cluttered by space debris.[16]

Figure 1. Monthly Number of Objects in Earth Orbit by Type



Source: National Aeronautics and Space Administration (NASA), *Monthly Number of Objects in Earth Orbit by Object Type*, 17 ORBITAL DEBRIS QUARTERLY NEWS 8 (2013).

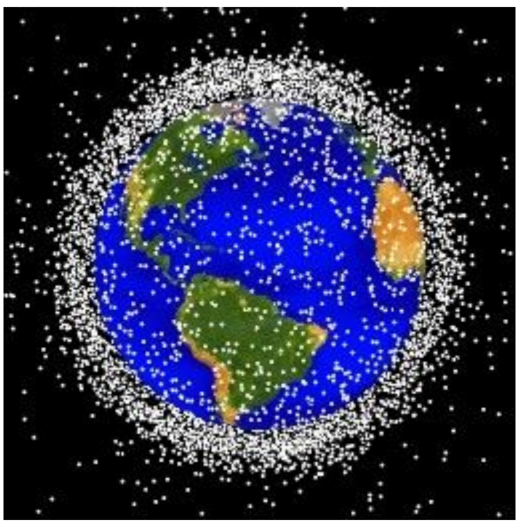
Note: The 2007 discontinuity is from Chinese anti-satellite test; the 2009 discontinuity is from Russia-Iridium collision.

Of the approximately 6,300 tons of space debris currently in orbit, approximately 2,700 tons are in LEO. Figure 2 shows a computer-generated image of currently tracked objects in space, of which 95% are debris. In particular, the LEO polar orbits are becoming congested.[17] This fact is troubling because almost half of all existing satellites are in LEO.[18] Currently, the

[16] *Id.* at 11–12.
[17] JOSEPH N. PELTON, SPACE DEBRIS AND OTHER THREATS FROM OUTER SPACE 8 (2013).
[18] Adilov et al., *supra* note 11, at 83.

only way debris can be removed is through atmospheric drag and the gravitational attraction of the Earth: debris is eventually destroyed by re-entry.[19] If the debris is in orbit close to the Earth—within 200 km of Earth's surface—it will be destroyed within a few days. However, at 800 km above the Earth, nearing space debris peak density, debris can remain in orbit for centuries. When approaching geosynchronous orbit (36,000 km), which comprises approximately 41% of existing satellites, debris can persist "essentially forever."[20]

Figure 2. Clutter from Space Debris



Source: National Aeronautics and Space Administration (NASA), *Orbital Debris: Graphics*, NASA ORBITAL DEBRIS PROGRAM OFFICE (October 2, 2012), http://orbitaldebris .jsc.nasa.gov/photogallery/beehives.html#leo.

Note: The image is from the vantage point of a low earth orbit.

Those rates of decay are accurate only if no new space debris is added in the interim. Given the previously mentioned possibility of a snowball effect, known among scholars as the

[19] PELTON, *supra* note 17, at 7–8.
[20] Adilov et al., *supra* note 11, at 83–85.

Kessler syndrome,[21] the rate of creation of new debris would completely overwhelm the debris' natural attrition. Liou and Johnson project that the amount of debris will approximately triple in the most congested orbits within the next 200 years, which will cause a tenfold increase in the probability of a collision.[22]

Current efforts to mitigate space debris are under the purview of various nations' space agencies and other administrative bodies. For example, in the United States, NASA in 1995 issued a set of procedures for limiting space debris by means of guidelines for deorbiting spacecraft at the end of their useful period of operation. The guidelines were expanded in 1997 when NASA, in conjunction with the Department of Defense, released the Debris Mitigation Standard Practices, which apply to government-operated or government-produced spacecraft.

For private organizations, the relevant administrative body is the Federal Aviation Administration, from which private parties must obtain a license before launching spacecraft. One of the conditions of obtaining a license is demonstrating the ability to comply with debris mitigation practices.[23] Internationally, the Inter-Agency Space Debris Coordination Committee (IADC), which was established in 1993, helps to promote cooperation in dealing with debris among the space agencies of the spacefaring nations. The IADC developed debris mitigation guidelines in 2002, and those guidelines were used in drafting the 2009 debris guidelines adopted by the United Nations Committee on the Peaceful Uses of Outer Space. Adoption of those guidelines is voluntary. Space agencies in France, Italy, Japan, Russia, the United

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[21] Donald K. Kessler & Burton G. Cour-Palais, *Collision Frequency of Artificial Satellites: The Creation of a Debris Belt*, 83 J. GEOPHYSICAL RES. 2637 (1978).
[22] Liou & Johnson, *supra* note 4.
[23] FABIO TRONCHETTI, FUNDAMENTALS OF SPACE LAW AND POLICY 21–22 (2013); JAMES CLAY MOLTZ, CROWDED ORBITS: COOPERATION AND CONFLICT IN SPACE 100 (2014).

Kingdom, and the United States have used the guidelines as inputs into their own debris mitigation standards.[24]

3. Space Debris and Orbital Access: An Economic Typology

Many who write about space debris, including several authors already cited, have concluded that the problems associated with space debris arise because access to orbit—getting a spacecraft from launch to its intended orbit—and the orbits themselves are public goods. In economics, *public good* has a very specific meaning. *Goods* are classified on the basis of two characteristics: whether they are rivalrous and whether they are excludable. A good is *rivalrous* if one person's consumption of it precludes the possibility of another person consuming that same good. A good is *excludable* if it is feasible to prevent those who do not buy the good from enjoying its benefits. If a good is both rivalrous and excludable, it is a *private good*.

Ordinary market mechanisms can adequately supply private goods. However, the two goods that are relevant to this paper—access to orbit and particular orbits (especially in LEO)—are not purely private goods.[25] Access to orbit is nonrivalrous; one party accessing orbit does not prevent another party from accessing orbit. Access to orbit is also nonexcludable; preventing others from enjoying the good is infeasible, given the good's existence.[26] Thus, access to orbit has both characteristics of a *public good*. Particular orbits are nonexcludable for the same reason. However, once one spacecraft is in a given orbit, another cannot occupy the same space at the same time. Especially when one considers the particularly crowded LEO polar orbits, classifying

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[24] TRONCHETTI, *supra* note 23. For a more in-depth discussion of international cooperation in space-related ventures, *see* FRANCIS LYALL & PAUL B. LARSEN, SPACE LAW: A TREATISE (2009).

[25] *Access to orbit* consists of the ability to launch a spacecraft into orbit. *Orbit* refers to one of many, many particular trajectories around Earth. Space debris can hamper both orbits and access to orbits.

[26] Of course, many nation-states' militaries have the capability to destroy spacecraft, but doing so is sufficiently costly in terms of damaging a nation's reputation, if nothing else. Thus, that scenario can safely be ignored in most circumstances.

those orbits as rivalrous at this point is reasonable. As such, orbits currently possess the characteristics of a *common pool resource*.

The difficulties posed by public goods and common pool resources are due chiefly to their nonexcludability. Given that no party can prevent other parties from enjoying the benefits of those goods, no party has an incentive to practice responsible stewardship. The space debris problem is thus a textbook example of the "tragedy of the commons."[27] Because nobody controls the resources and the rights associated therewith, especially the right of exclusion, nobody has any incentive to undertake the effort necessary to prevent future debris buildup. In addition, nobody has any incentive to economize activities, such as future spacecraft launches that further contribute to space debris clutter.[28] Of course, when all parties interested in space access act according to this logic, the unintended result is an outcome—polluted orbital space—in which everyone is worse off. This unfortunate outcome is an example of what economists call *market failure*—a situation where the privately beneficial strategy differs from the socially optimal strategy.

In this situation, the actions of each party are imposing costs on other parties, in the form of leaving orbit more crowded than it previously was, without the other parties' consent. Since the writings of the economist A. C. Pigou, the standard corrective to such behavior is public policy that forces actors to consider the costs, or negative externalities, they are imposing on others.[29] Imposing a tax, or some other fee, on contributors to the orbital debris problem can help prevent those costs. By raising the private cost of further polluting orbit, potential orbital polluters will bear both the private and the social costs of their actions, resulting in a more efficient allocation of resources. Adilov et al. (2015) adopt such a strategy when they provide a

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[27] Garrett Hardin, *The Tragedy of the Commons*, 162 SCI. 1243 (1968).
[28] *See* Adilov et al., *supra* note 8.
[29] ARTHUR C. PIGOU, THE ECONOMICS OF WELFARE (1932).

mathematical model of the space debris situation and derive an optimal Pigouvian tax. That tax is intended to offset externalities. For example, if the production of a good is associated with negative externalities—such as debris produced from launching spacecraft—then, in theory, the public sector can incentivize the producer to take those costs into account by taxing the producer, with the size of the tax set equal to the size of the negative externality.

Although attractive in theory, Pigouvian taxes encounter two serious problems. First is the knowledge problem: it is difficult to believe that the public sector has the knowledge necessary to implement an optimally sized tax. Such knowledge would require heroic assumptions about the ability of regulators to ascertain the state of currently existing markets relative to their perfectly efficient state. The second is the incentive problem: even if regulators do have the knowledge necessary to solve the externality problem, fixing the issue may not be in their interest. Like market actors, public-sector actors are not angels. They have their own sets of beliefs and goals, and those values will only imperfectly align with promoting economic efficiency. Market actors promote efficiency because of the discipline imposed by the market profit-and-loss system; public-sector actors face much less rigorous constraints.

An alternative solution to externalities problems, as well as tragedies of the commons more generally, merits exploration. Ronald Coase famously pointed out that all externalities problems are really property rights problems.[30] One party imposing a cost on another party is actually a conflict of property rights. Clearly determining the violated party in property rights conflicts is frequently challenging. According to Coase, this is why the legal system is so important. By sorting out property rights disputes, the legal system corrects ambiguities about the underlying property rights framework. Once property rights are more completely specified,

[30] Ronald Coase, *The Problem of Social Cost*, 3 J.L. & ECON. 1 (1960).

determining whose rights are infringing whose and which party has the burden of ceasing the damaging activities will be easier. Because externalities problems can frequently be corrected by more adequately defining property rights—a solution that sidesteps several of the difficulties associated with a Pigouvian tax[31]—many economists favor a more explicit definition of property rights as a solution to externalities problems.

The fact that no regime of private property rights for orbital access and for orbits exists does seem to be the proximate cause of the space debris problem. If the saying "that which nobody owns, nobody will care for" is true, then one solution may be to grant ownership rights to various launch trajectories and orbits. However, even putting aside the obvious difficulties in the face of existing international law,[32] whether a private property rights regime is feasible is not clear. How would property rights to a launch trajectory and an orbital slot be defined? Would rights be associated with a physical volume of space? If so, how much? Such a solution quickly encounters many serious difficulties.[33] Dealing with the tragedy of the commons posed by space debris in this manner runs into many of the same problems associated with dealing with terrestrial pollution, such as greenhouse gas creation. Demsetz's realization quickly becomes more evident: if the cost of defining and enforcing property rights is too high, it may be efficient for the rights not to exist.[34]

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[31] A notable difficulty is correctly sizing the tax. Getting the tax right is easy to do in an economic model, where all parameters and variables are fully specified. In the real world, however, where the values of the underlying parameters are unclear, calculating the size of a corrective tax can be difficult.

[32] The 1967 Outer Space Treaty, signed by all spacefaring nations, prohibits the extension of territorial sovereignty to outer space and the celestial bodies, which makes the legal basis for private property rights in outer space unclear. Alexander W. Salter & Peter T. Leeson, *Celestial Anarchy: A Threat to Outer Space Commerce?*, 34 CATO J. 581, 581–84 (2014).

[33] It is probable that such rights could not be defined even in principle. However, even if they could, there would be tremendous difficulties in securing international support for the recognition of such rights, for reasons discussed later in the paper.

[34] Harold Demsetz, *Towards a Theory of Property Rights*, 57 AM. ECON. REV. 347 (1967).

But it may be too soon to dismiss Coasian solutions. Another implication of Coase is that legal authorities, by specifying who is responsible for dealing with externalities problems, also indirectly influence overall economic efficiency. If a legal authority places the burden for adjusting behavior on a party who is not the least-cost bearer of that burden, the legal authority has inefficiently allocated legal responsibilities. Overall cost minimization associated with resource allocation is a desirable goal—that is, the lower the costs associated with a given allocation of resources, the more resources are leftover to satisfy other wants and desires. Thus, a legal authority declaring who bears the burden of coping with space debris can still be worthwhile, even without establishing fully specified property rights to orbital access and trajectories.

4. The Good in Question: A Further Specification

Consider a hypothetical legal rule that places the burden for coping with space debris entirely on private parties. Such a rule immediately seems irresponsible because the magnitude of the commons problem suggests private-sector solutions are infeasible. Writers about space debris, including many of those cited earlier, agree with this line of reasoning. However, many problems involving public goods provision that economists and other social commenters have historically considered "impossible" for the private sector to solve have, in fact, been solved by private actors. Coase's literature about the theoretical impossibility but historical reality of private lighthouses is perhaps the most famous example.[35] Clearly, no private actor has adequately dealt with space debris in the past, but considering the hypothetical in which the burden rests with private actors can at least mitigate sweeping statements about comparative institutional efficacy.

[35] Ronald Coase, *The Lighthouse in Economics*, J.L. & ECON. 357 (1974).

The first thing to note is that space debris poses a problem primarily because of the possibility of destroying useful spacecraft. If space debris could not damage spacecraft, it would not pose a problem. The costs of space debris are directly linked to the damage that space debris can cause. As such, two goods questions arise: How can orbital access and orbital space be uncluttered, and how can spacecraft be more robust against collisions? Investments in robustness may, at the margin, lessen the costs associated with the lack of open space, even if that solution does not actually address the issue of existing space debris. A clearly announced legal rule placing the financial burden (of coping with spacecraft destroyed by debris) on private actors would incentivize investment in technologies that would help cope with existing debris. Examples of such technologies include using stronger materials for shielding against debris and increasing the maneuverability of spacecraft in the event of an expected collision with a piece of debris.

The second thing to note is that a sizeable market for insuring spacecraft from damage already exists. Market premiums for insurance against space risk totaled at $800 million in 2011, while losses arising from damage totaled at $600 million.[36] Insurance can be purchased to cover (a) the prelaunch period, which includes construction and transportation to the launch location; (b) the launch period, which covers the launch and ends with the spacecraft's placement in orbit; and (c) the in-orbit period, which covers damage and technical failure once the spacecraft has reached its intended orbit.[37]

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[36] Allianz, *Space Risks: A New Generation of Challenges* 2 (Allianz Global Corporate and Specialty, Working Paper No. WP/IC/0612, 2012), *available at* https://www.allianz.com/v_1342876324000/media/press/document/agcs_space_risks_white_paper.pdf.

[37] Federal Aviation Administration, *Commercial Space and Launch Insurance: Current Market and Future Outlook* (Federal Aviation Administration, Quarterly Launch Report, Fourth Quarter, 2002), *available at* https://www.faa.gov/about/office_org/headquarters_offices/ast/media/q42002.pdf.

Parties interested in placing spacecraft in orbit are already able to insure against property damage caused by collisions with space debris.[38] Insurance is most useful in protecting against very small possibilities of extreme costs, as in the case of catastrophic health insurance. Destruction of spacecraft as a result of a collision with existing debris falls squarely within this category. Although appropriate insurance premiums are becoming more difficult to forecast because of rising launch values and upward revisions on the probability of collision,[39] market mechanisms can still calculate premiums that enable both sides of the market to capture gains from trade, just as in any other insurance market.

The cost to society of coping with space debris in a legal-institutional environment that places the burden entirely on private actors is equal to the value of the resources used up by these actors, both for mitigation and liability avoidance. If some alternative legal-institutional arrangement existed whereby the costs associated with investing in technologies that are specifically oriented to protect spacecraft against space debris and specifically associated with maintaining a viable insurance market could be reduced, then that alternative would be preferable from the standpoint of economic efficiency. However, even under an ideal institutional environment, it is uncertain whether a purely private-sector response would be sufficient to cope with the space debris problem.[40]

Even if private actors invest in more robust and more maneuverable spacecraft and if they increase the amount of resources devoted to the insurance market, some spacecraft would still occasionally be destroyed. Thus, space debris, on net, would increase. This increase is

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[38] Denis Bensoussan, Satellite Vulnerability to Space Debris Risk, Presentation at the Sixth International Association for Shell and Spatial Structures Conference (May 21–23, 2013), *available at* http://iaassconference 2013.space-safety.org/wp-content/uploads/sites/19/2013/06/1440_Bensoussan.pdf.

[39] *See* Allianz, *supra* note 36.

[40] Even if some public-sector role is necessary, that role may not be to directly act on or within the market to ameliorate the space debris problem. Instead, the public sector should focus on crafting *rules* that incentivize private actors to respond to the problem appropriately. This alternative will be discussed further in subsequent sections.

problematic precisely because of the already-mentioned possibility of the Kessler syndrome—the snowballing effect of debris, which will sufficiently clutter orbit so as to render its use extremely difficult. If the problem progresses to this degree, the costs of dealing with space debris in the future will be high. The more cluttered orbital access and specific orbits become, the higher the costs the private sector must incur to prevent damage. Also, the more probable a collision becomes, the less effective insurance becomes as a coping mechanism. If incurring damage becomes a certainty, those costs become impossible to insure.

To summarize thus far, the space debris problem exists because of externalities that some spacefaring agents impose on others and because of the tragedy of the commons. At the general level, the most reliable solution to such problems is the establishment and enforcement of private property rights. This solution appears infeasible in this case, and a legal rule placing the burden entirely on private actors would probably also be insufficient to cope with the dangers of excessively cluttered orbital access and trajectories.

Taken together, those factors suggest that public policy plays a role in mitigating the space debris problem. Economically, this suggestion means the total costs posed by the problem would probably be lower in a situation with some public policy response toward mitigation. Although the writers already cited in this paper have advanced this position without a serious discussion of whether a purely private response is feasible, those writers' conclusion nonetheless appears correct. There is current justification for existing rules requiring the deorbiting of spacecraft after their useful lifespan, for example. In addition, some sort of user fee, as proposed by Adilov et al.,[41] may be appropriate. However, the knowledge problem concerning the correct size of the tax will render rational pricing difficult, if not impossible. Also, the implementation

[41] Adilov et al., *supra* note 8.

process, as with all well-intended public-sector responses, may be susceptible to capture by special interests. Given the lucrative opportunities associated with future outer space commerce,[42] the implementation process is unlikely to be so wasteful as to exhaust the prospective wealth gains. However, a realistic appraisal of the public sector is still necessary to keep implementation costs to a minimum.[43]

5. Mitigation vs. Removal

Sections 4 and 5 focused on dealing with the existing space debris scenario. An alternative to debris mitigation is debris removal—actively depolluting orbital access and cluttered orbits. Currently, many technological proposals for removing space debris exist, and they usually involve pushing large pieces of debris into a decaying orbit or sometimes into a parking orbit, which would be far enough away from the earth to render collision during orbital access virtually impossible. I will not survey those technologies or discuss their relative merits. Instead, I will focus on the legal difficulties in current international law associated with debris removal and the costs those difficulties present for all future removal projects, irrespective of technology.

Relying on international law to create an environment conducive to space debris removal initially seems promising. The Virginia school of political economy has convincingly shown the importance of political-legal institutions in creating the incentives that determine whether those

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[42] *See* SPACE: THE FREE MARKET FRONTIER (Edward L. Hudgins ed., 2003); LEWIS D. SOLOMON, THE PRIVATIZATION OF SPACE EXPLORATION: BUSINESS, TECHNOLOGY, LAW AND POLICY (2012); Salter & Leeson, *supra* note 32; JOHN S. LEWIS, ASTEROID MINING 101: WEALTH FOR THE NEW SPACE ECONOMY (2015).

[43] Normally, the lack of incentives for political bureaucracies to economize on resources used in fulfilling their mandate is a significant argument against solutions that overly rely on public policy. *See* LUDWIG VON MISES, BUREAUCRACY (1994); GORDON TULLOCK, BUREAUCRACY (2005); RANDY T. SIMMONS, BEYOND POLITICS: THE ROOTS OF GOVERNMENT FAILURE (2011). Given the massive potential of wealth creation from space commerce, it would be difficult in this specific case for the public sector to exhaust the potential wealth gains because of inefficient policy crafting.

who act within those institutions behave cooperatively or predatorily.[44] In the context of space debris, the role of nation-states, or their space agencies, would be to create an international legal framework that clearly specifies the rules that will govern space debris removal and the interactions in space more generally. The certainty afforded by clear and nondiscriminatory[45] rules would enable the parties of the space debris "social contract" to use efficient strategies for coping with space debris. However, this ideal result is, in practice, far from certain. To borrow a concept from Buchanan and Tullock's framework,[46] the costs of amending the rules in the case of international space law are exceptionally high. Although a contract is beneficial in that it prevents stronger nation-states from imposing their will on weaker nation-states, it also creates incentives for the main spacefaring nations to block reforms that are overall welfare-enhancing but that do not sufficiently or directly benefit the stronger nations.

The 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (more commonly known as the Outer Space Treaty) is the foundation for current international space law.[47] All major spacefaring nations are signatories. Article VIII of this treaty is the largest legal barrier to space debris removal efforts. This article stipulates that parties to the treaty retain jurisdiction over objects they launch into space, whether in orbit or on a celestial body such as the Moon. This article means that American organizations, whether private firms or the government, cannot remove pieces of Chinese or Russian debris without the permission of

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[44] *See* JAMES M. BUCHANAN & GORDON TULLOCK, THE CALCULUS OF CONSENT: LOGICAL FOUNDATIONS OF CONSTITUTIONAL DEMOCRACY (1962); GEOFFREY BRENNAN & JAMES M. BUCHANAN, THE REASON OF RULES: CONSTITUTIONAL POLITICAL ECONOMY (2000).

[45] In this context, *nondiscriminatory* most closely means there are no special privileges for some parties that place burdens on other parties. JAMES M. BUCHANAN & ROGER D. CONGLETON, POLITICS BY PRINCIPLE, NOT INTEREST: TOWARDS NONDISCRIMINATORY DEMOCRACY (2000).

[46] BUCHANAN & TULLOCK, *supra* note 44.

[47] The full text of the treaty can be found online at http://www.unoosa.org/oosa/SpaceLaw/outerspt.html.

their respective governments. Perhaps contrary to intuition, consent will probably not be easy to secure.

A major difficulty lies in the realization that much debris is valuable scrap material that is *already in orbit*. A significant fraction of the costs associated with putting spacecraft in orbit comes from escaping Earth's gravity well. The presence of valuable material already in space can justifiably be claimed as a valuable resource for repairs to current spacecraft and eventual manufacturing in space. As an example, approximately 1,000 tons of aluminum orbit as debris from the upper stages of launch vehicles alone. Launching those materials into orbit could cost between $5 billion and $10 billion and would take several years.[48] Another difficulty lies in the fact that no definition of space debris is currently accepted internationally. Although this ambiguity may appear purely semantic, resolving it does pose some legal difficulties. Doing so would require consensus among the spacefaring nations. The negotiation process for obtaining consent would be costly.

Less obvious, but still important, is the 1972 Convention on International Liability for Damage Caused by Space Objects, normally referred to as the Liability Convention. The Liability Convention expanded on the issue of liability in Article VII of the Outer Space Treaty. Under the Liability Convention, any government "shall be absolutely liable to pay compensation for damage caused by its space objects on the surface of the Earth or to aircraft, and liable for damage due to its faults in space."[49] In other words, if a US party attempts to remove debris and accidentally damages another nation's space objects, the US government would be liable for damages. More generally, because launching states would bear costs associated with accidents during debris removal, those states may be unwilling to participate in or permit such efforts. In

[48] Levin & Carroll, *supra* note 5, at 13.
[49] http://www.unoosa.org/oosa/SpaceLaw/liability.html.

theory, insurance can partly remediate the costs, but that remediation would still make debris removal engagement less appealing.

A global effort to remediate debris would, by necessity, involve the three major spacefaring nations: the United States, Russia, and China.[50] However, any effort would also require—at a minimum—a significant clarification and—at most—a complete overhaul of existing space law.[51] One cannot assume that parties to the necessary political bargains would limit parleying to space-related issues. Agreements between sovereign nation-states must be self-enforcing.[52] To secure consent, various parties to the change in the international legal-institutional framework may bargain strategically and may hold out for unrelated concessions as a way of maximizing private surplus. The costs, especially the decision-making costs, of changing the legal framework to secure a global response to a global commons problem are potentially quite high.

Fortunately, private and public actors may be able to act unilaterally under the purview of a given nation-state (as Ansdell recommends[53]) and, in a manner, may be unlikely to run afoul of international legal issues. It bears repeating that the primary problem posed by space debris is the possibility of the Kessler syndrome. A complete removal of existing debris is unnecessary; instead, mitigation and removal together simply need to keep orbital access and trajectories sufficiently uncluttered to prevent reaching the congestion "tipping point."

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[50] Currently, the main efforts being made on this front take place within the IADC (http://iadc-online.org/index.cgi ?item=docs_pub), of which the US, Russian, and Chinese space agencies are members. The IADC's main activities are research, debris monitoring, and risk assessment. Efforts at mitigation—especially removal—are still nascent.
[51] Steven A. Hildreth & Allison Arnold, *Threats to U.S. National Security Interests in Space: Orbital Debris Mitigation and Removal* 11–12 (Congressional Research Service Report No. R43353, 2014), *available at* http://www.fas.org/sgp/crs/natsec/R43353.pdf.
[52] *See* Alexander W. Salter, *Sovereignty as Exchange* 581–84 (Berry College, Working Paper, 2014), *available at* http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2535471.
[53] Ansdell, *supra* note 2.

Liou, Johnson, and Hill estimate that if five sufficiently large pieces of debris are removed per year over the next 100 years, orbital access and LEO can be stabilized.[54] However, stabilization is conditional on (a) all future launches, including non-US launches, complying with NASA guidelines concerning deorbiting and (b) no new major collisions creating new debris in the interim. Although the IADC proposes similar guidelines, those guidelines are nonbinding and current global compliance is below the NASA/IADC threshold.[55] Current spacefaring nations could use existing international forums to pressure noncompliers. Securing a solution in this manner would almost certainly be less costly than making a major change to the foundations of existing international space law. Nevertheless, mutual agreement is required, and up-and-coming national actors with spacefaring ambitions may be unwilling to bear the costs associated with compliance.

Assuming a nation-state, even under current international space law, wished to supervise a space debris removal mission, how would it do so? A crucial question concerns the division of responsibility between the private and public sectors. Some impetus would almost certainly fall on the public sector. At a minimum, the public sector's role involves further clarification of the legal framework—the "rules of the game"—for space debris at the national level. Using the United States as an example, clarifying the framework may be as simple as announcing that the law of salvage, as it exists in current maritime law, will apply to its own space debris. In other words, any private party under the jurisdiction of the United

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[54] Jer-Chyi Liou, Nicholas L. Johnson & Nicholas M. Hill, *Controlling the Growth of Future LEO Debris Populations with Active Debris Removal*, 66 ACTA ASTRONAUTICA 648 (2010).

[55] A 2013 IADC report, supported by six member space agencies, simulated future space debris growth assuming 90% guideline compliance. In the conclusion, the report states the compliance assumptions made in the study "is certainly higher than the current reality," Inter-Agency Space Debris Coordination Committee (IADC), *Stability of the Future LEO Environment*, 17 (IADC Working Paper), available at http://www.iadc-online.org/Documents/IADC-2012-08,%20Rev%201,%20Stability%20of%20Future%20LEO%20Environment.pdf. However, the report does not state which nations are below the compliance threshold.

States that wishes to remove US space debris may do so and is entitled to whatever value is recovered thereby.

Companies such as Deep Space Industries and Planetary Resources are planning long-term asteroid mining projects, which will probably require space infrastructure for in-situ manufacturing or, at least, repairs. Because much debris contains valuable material, the chance to access such material without bearing the costs ordinarily associated with bringing it into orbit can be a significant incentive. Building this infrastructure would involve moving existing debris to a parking orbit rather than destroying it, of course. Most important, those companies would be able to remove clearly identifiable US space debris only, and the US government would be liable for any accidents caused by removal operations that damage other nations' space objects.

A more involved response would have private firms bidding on contracts for removal or destruction of debris. Given the strong incentives in the private sector for keeping costs low, the private sector should probably handle much of the manufacturing and assembly, as SpaceX (a private builder of launch vehicles) does in its dealings with NASA. To the extent multiple firms invest in the competitive bidding process to be awarded a lucrative debris-removal contract, resources may be needlessly wasted, similar to the process described by Tullock in his seminal essay about rent-seeking.[56] However, this objection assumes we know ex ante which firm among the bidders is best suited for the task.

To the extent that the competitive bidding process is viewed as a mechanism for discovering which firm is the least-cost provider, the process itself produces valuable information. In this scenario, however, the crucial difficulty will be deciding the value of the contract to be auctioned off. Too low a value will not provide sufficient incentives for

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[56] Gordon Tullock, *The Welfare Costs of Tariffs, Monopolies, and Theft*, 5 ECON. INQUIRY 224 (1967).

production, and too high a value will involve wasted resources. Pricing those sorts of contracts is as difficult as correctly pricing an optimal externality-correcting tax. Thankfully, the pricing process can be avoided not by auctioning off a contract, as is standard in public-sector dealings with corporations such as Boeing and Raytheon, but simply by auctioning off the right to claim space debris. The value of the space debris would determine the value of the right won by auction. This sort of pricing process retains the knowledge-generating features of competitive bidding without burdening the public sector with the responsibility for deciding the optimal contract value.

Unilateral action on the part of a major spacefaring nation is only a partial solution. More comprehensive approaches will have to grapple with the costly process of amending, if not rewriting, international space law in a manner that clarifies under what situations individuals can claim private property rights to debris and celestial bodies, when they are liable for damages to state and nonstate actors, and so on. Again, amending laws will be difficult precisely because of nations' propensity to bargain strategically, perhaps using the value of the materials in their space debris as justification for holdout behavior. Although economically it is probable that, absent political interference, incentive-aligning institutions would emerge to cope with some of those difficulties,[57] complete passivity on the part of state actors is infeasible politically. Current international space law is centered on state actors' responsibility for public and private organizations under their jurisdiction. Even a complete overhaul of international space law—so that space becomes the "free market frontier,"[58]—would require some state actors to bring about such a scenario.

[57] Salter & Leeson, *supra* note 32.
[58] Hudgins, *supra* note 42.

6. Conclusion

My analysis of the space debris problem was not intended to offer a concrete proposal for a solution. Technologically, economically, and legally, it is still too soon for such a proposal. Instead, the preceding analysis should help clarify the exact nature of the problem and should help nations understand what problems need to be overcome.

The global scope of the externality associated with space debris suggests that actions by individual spacefaring nation-states are important—and perhaps necessary—but are not sufficient. Although compliance with deorbiting guidelines and imposition of a user fee to raise the private cost of launching new spacecraft are justifiable policies in the immediate future, those solutions are unlikely to stave off the troubling possibility of the Kessler syndrome. Mitigation needs to be complemented by removal. Some sort of international cooperation will likely be a part of any long-term solution, but the costs of negotiating such an agreement are, prospectively, very costly. Nonetheless, without a stable and clear legal framework, little progress is being made about the space debris problem.

Development of the international legal framework will be crucial to provide public and private actors with an incentive to remove debris. In many social situations, uncertainty about the fundamental "rules of the game" can be crippling.[59] Without clarifying existing rules in cases where they are ambiguous and without crafting new rules that are incentive-compatible when the situation calls for it, the institutional structure required for actors to deal with space debris—and hence capture the wealth-creating possibilities of space—will not exist. Practically speaking, given current international law and the scope of the commons problem associated with debris, public authorities will probably have to play some role in facilitating the crafting of the necessary rules.

[59] BRENNAN & BUCHANAN, *supra* note 44.

In closing, the economic perspective adopted in this paper treated private-sector responses and public-sector responses as alternative ways of coping with space debris, although the responses are certainly complementary in several ways. However, this private-public dichotomy, while appropriate for highlighting the nuances of the problem, should not be taken as absolute. Elinor Ostrom's significant contributions[60] to social science show that alternative institutional responses may be classified along a spectrum that transcends the private-public dichotomy.

Many institutions for governing common pool resources and public goods resemble neither markets nor governments; rather, they contain features of both. Those institutions emerge from repeated strategies of local resource users who are interested in securing maximal gains from trade. Of particular interest, Ostrom identifies the kinds of rules that governance institutions must devise to motivate users to behave responsibly with respect to the commons.[61]

As Adilov et al. recognize, the global nature of the space debris commons and hence the externality problem render it unlikely that the same features characterizing the emergence of institutions to govern local commons will also result in the emergence of effective institutions for space debris mitigation and removal.[62] Nation-states are currently the active—indeed, the main—players in the space environment, and all existing institutions are oriented around them as legitimate actors. Because of this, the practices that develop to deal with space debris will more closely resemble a private-public dichotomy than in other commons governance situations.

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[60] Elinor Ostrom, *Beyond Markets and States: Polycentric Governance of Complex Systems*, 100 AM. ECON. REV. 641 (2010). *See also* ELINOR OSTROM, GOVERNING THE COMMONS: THE EVOLUTION OF INSTITUTIONS FOR COLLECTIVE ACTION (1990).
[61] OSTROM, GOVERNING THE COMMONS, *supra* note 60, at 653.
[62] Adilov et al., *supra* note 8.

Nonetheless, Ostrom's work is crucial because it highlights what problems that *any* set of institutions must solve. A polycentric governance structure for debris removal and for outer space governance more generally may, in fact, evolve. But the structure must necessarily begin with private and public actors (a) establishing concrete strategies to cope with the space debris problem as best they can, given the institutional framework, and (b) modifying the institutional framework in ways acceptable to all interested parties.