Page 1086 - 1094 **DOI:** *https://doij.org/10.10000/IJLMH.1110501*

INTERNATIONAL JOURNAL OF LAW MANAGEMENT & HUMANITIES

[ISSN 2581-5369]

Volume 8 | Issue 4

2025

Space Debris and Environmental Hazards: A Legal Analysis of Orbital Pollution and Global Regulatory Challenges

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ABSTRACT

The exponential increase in space debris presents a growing threat not only to the functional spacecraft and satellite infrastructure but also to the orbital environment. With the increase in space activities originating from commercial ventures and states, Earth's orbital space has become congested and increasingly unsafe with the accumulation of defunct satellites, fragments of spent rockets, and debris created by collisions. The paper touches upon space debris from an environmental law perspective and assesses whether the current legal framework can deal with this emerging problem.

Though treaties like the Outer Space Treaty (1967) and the Liability Convention (1972) provide the basic international norms for governance of activities in space, they do not contain any binding obligations for debris mitigation or environmental protection in outer space. Other non-binding instruments-the UNCOPUOS Space Debris Mitigation Guidelines and the Long-Term Sustainability Guidelines-remain mere recommendations without enforcement capacity. Principles of environmental law like precautionary principle, polluter pays principle, and sustainable development have hardly found any application in space governance due to jurisdiction

It also surveys national approaches, highlighting how local regulations are working against global efforts due to their disparities. In the vacuum of an enforceable international treaty regulating space debris, this regulatory vacuum might lead to on-orbit environmental degradation similar to what we have witnessed on Earth. The study ends by proposing a legal framework in which space law could be integrated with environmental principles to advance the enactment of a binding multilateral treaty and universally accepted standards for debris mitigation with the inclusion of environmental impact assessments. Some remediation of orbital pollution as an environmental hazard is necessitated for the sustenance of space activities into the future.

Keywords: *Space debris, orbital pollution, environmental law, outer space law, sustainable space activities*

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 [ISSN 2581-5369]

I. INTRODUCTION

In recent decades, outer space has transformed from a realm of scientific exploration in the classic sense to a cluttered, highly competitive venue for commercial, military, and civil activities. This increased number of space launches and satellite deployments has resulted in a dangerous accumulation of debris-compromised satellites, defunct spacecraft and spent rocket stages, consequent from collisions or explosions. The greater part of these debris pieces occupies LEO, wherein important communication, weather, navigation, and defense satellites operate.

Space debris incumbents are not only technical or operational issues; they have now turned into serious environmental threats. With more than 36,000 trackable objects bigger than 10 cm and millions of smaller debris pieces, it is constantly threatening collisions with active satellites, space stations, and human life in space. The Kessler Syndrome, in which cascades of collisions create an unsustainable orbital environment, highlights the urgency with which this problem is being considered. Outer space is most often pictured as limitless, but the operative orbital zones-areas in which orbit can be achieved and RMB-either are limited or ever increasing with traffic. This really brings space debris within the purview of environmental law, effectively classifying it as orbital pollution. But, unlike air, water, or land on Earth, the orbital environment still lacks sufficient regulation, with few enforceable obligations binding on States.

This paper will study how space debris is covered by national and international legal frameworks and try to determine if the existing principles of environmental law can be significatively extended to solve this burgeoning dilemma in the outermost fringes of our Earth.

II. UNDERSTANDING SPACE DEBRIS AS AN ENVIRONMENTAL HAZARD

The problem of space debris has become a serious environmental hazard with legal, political, and ecological ramifications. Space debris is described as anything manmade in Earth's orbit that no longer serves any useful purpose-thirty redundant satellites, rocket stages that have been expended, fragments produced in collision or explosion. The danger caused by the accumulation of this orbital waste grows in direct proportion to humanity's increasing dependence on outer space infrastructure. The problem becomes much more severe in the Low Earth Orbit where most of the satellites reside, and the threat of debris-collision cascading endangers the very sustainability of outer space.

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One of the most serious immediate environmental and safety hazards space debris poses is the possibility of impact against an operational spacecraft. Objects bigger than about 1 cm can cause catastrophic damage at relative velocities in orbit that often exceed 28,000 km/h. In 2009, a defunct Russian satellite, Cosmos 2251, collided with an operational American one by the name of Iridium 33, generating over 2,000 pieces of trackable debris and thousands of untraceable fragments. Memory-based definitions with superscript indicators do a good job here[2]. Proposed in 1978 by NASA scientist Donald J. Kessler, the Kessler Syndrome scenario is one where the object population in LEO becomes so densely packed that every collision creates more debris, initiating a self-sustaining chain reaction of destruction that would keep space unusable for generations[3]. The syndrome is no longer hypothetical; with the increasing launch of mega-constellations such as Starlink by SpaceX, the risk of orbital saturation increases exponentially. Unlike Earthly pollutants, it does not decay or dissipate by nature-the case with the debris: oppositely, at much higher altitudes, debris can stay in orbit for centuries even! Objects above 1,000 kilometers altitude, for example, may endure for well over a century[4]. Hence, long-term contamination of usable space orbits seriously challenges space activities of the future.

The effects of contamination cascade: satellite operators are now forced to dodge debris by maneuvering their satellites, thereby increasing costs, shortening satellite lifespan, and consuming fuel. Also doing harm to the situation: collisions generate more debris. The ESA has warned that an uncontrolled increase of orbital debris might soon outgrow the ability to address its mitigation or avoidance methods[5]. Much of the debris burns up when they re-enter Earth's atmosphere; however, the larger fragments can make their way to Earth's surface. The 1978 re-entry of the Soviet satellite Kosmos 954, equipped with a nuclear reactor, spread radioactive substances all over Northern Canada, necessitating an international cleanup and liability claim under the 1972 Liability Convention[6].

Environmental issues are not limited solely to Earth; they also extend to the upper atmosphere. According to recent research, re-entering spacecraft might be releasing aluminum oxide particles and other pollutants into the stratosphere and mesosphere that might play a

[2] Johnson, N. L. (2010). Space Debris: Assessing Risk and Responsibility. *Science and Global Security*, 18(4), 222–229.
[3] Kessler, D. J., & Cour-Palais, B. G. (1978). Collision Frequency of Artificial Satellites: The Creation of a Debris Belt. Journal of Geophysical Research, 83(A6), 2637–2646.
[4] United Nations Office for Outer Space Affairs (UNOOSA). (2022). *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*.
[5] European Space Agency (ESA). (2021). *Space Environment Report*.
[6] Government of Canada. (1979). *Agreement Between Canada and the USSR on the Kosmos 954 Incident*.

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crucial role in ozone chemistry and atmospheric dynamics[7]. While still being researched, the sheer accumulation of satellite constellations and uncontrolled re-entries is already raising alarm in terms of atmospheric pollution[8]. In the past, environmental hazards used to be contained to the lands and waters. Today, orbital zones are considered free environmental commons. Outer space is outside sovereign control by any state, unlike land or airspace, thereby imposing hurdles on its legal administration. The adverse environmental impacts emanating from space debris strengthen the case setting the environment of space as a micro-ecosystem that appears to be fragile and in dire need of international cooperation and regulation, much in the same way as climate change or ocean environment is.

Thus, when environmental law scholars and environmental policymakers speak of "orbital pollution," they bring to bear the principles with which they are familiar-cautious principle, polluters pay principle-for the unfamiliar milieu of space governance under this term. A change of this nature needs to be instituted in the discourse if the global community seeks to develop a tangible and actionable framework of international law addressing the worsening orbital crisis.

III. INTERNATIONAL LEGAL FRAMEWORK

Outer space regulation is mainly an international matter, with a series of treaties for its governance. These treaties were developed by UNCOPUOS. The most fundamental treaty is the Outer Space Treaty, adopted in 1967, whose formal name is The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies. The treaty states that outer space shall be free to all states and that national appropriation or sovereignty over any part of space shall not be allowed. It stands almost silent on matters of space debris, without binding obligations on states to reduce the proliferation of or prevent generating such debris[9]. The Liability Convention of 1972 is another important legal instrument that establishes a liability regime under which a state is held liable for damage caused by space objects. By way of this liability regime, launching states are held absolutely liable for damage caused on Earth and liable due to fault for damage caused elsewhere in outer space[10]. But, the Liability Convention is reactive in nature—it

[7] Ross, M. N., Toohey, D. W., & Peinemann, M. (2009). Limits on the Space Launch Market Related to Stratospheric Ozone Depletion. *Astropolitics*, 7(1), 50–82.
[8] Zyla, B. (2023). Environmental Consequences of Mega-Constellations. *International Journal of Environmental Studies*, 80(1), 101–118.
[9] United Nations. (1967). *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*, Article I–IX.
[10] United Nations. (1972). *Convention on International Liability for Damage Caused by Space Objects*, Article II–IV.

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provides for redress mechanisms once the damage has taken place, but there is nothing in it for debris prevention, monitoring, or mitigation[11].

The Convention on Registration of Objects Launched into Outer Space (1976) attempts to increase transparency and traceability by obliging states to provide information about their space objects to the UN[12]. Therefore, while this in itself helps with tracking space traffic, it nevertheless does not concern itself with debris, nor does it set standards for the safety of launch, operation, or de-orbit procedures. Recognizing these gaps, UNCOPUOS developed non-binding guidelines for the management of the space environment. The 2007 Space Debris Mitigation Guidelines, formed on a basis of work by the Inter-Agency Space Debris Coordination Committee (IADC), recommend best practices, including ensuring the release of debris is limited in the course of normal operations, avoiding any intentional destruction of space objects, and designing space systems to prevent accidental explosions[13]. These guidelines, albeit generally agreed upon in principle, do not have the force of law and so may only be voluntarily adhered to.

In addition, in 2019, UNCOPUOS adopted the Long-Term Sustainability (LTS) Guidelines, which present a broader way for responsible behavior in space. These include recommendations in space traffic management, debris monitoring, information sharing, and capacity building[14]. Yet again, it is argued these are norms that are non-binding, evolving out of consensus-based diplomacy rather than out of coercive legal obligations.

IV. Legal Gaps and Challenges

Despite the growing threat posed by space debris, the current international legal framework remains inadequate, fragmented, and largely unenforceable. One of the most critical shortcomings is the absence of a binding, multilateral treaty that specifically regulates the generation, mitigation, and remediation of space debris. Existing instruments—such as the Outer Space Treaty (1967) and the Liability Convention (1972)—offer general principles and post-damage compensation mechanisms but lack proactive and preventive obligations[15]. Furthermore, UNCOPUOS guidelines on debris mitigation and sustainability, though progressive in scope, are soft law instruments with no legal compulsion[2]. As such, compliance is voluntary and varies widely among states.

[11] Lyall, F., & Larsen, P. B. (2018). *Space Law: A Treatise*. Routledge. pp. 117–123.
[12] United Nations. (1976). *Convention on Registration of Objects Launched into Outer Space*, Articles II–IV.
[13] UNCOPUOS. (2007). *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space*.
[14] UNCOPUOS. (2019). *Guidelines for the Long-term Sustainability of Outer Space Activities*.
[15] United Nations. (1967). *Outer Space Treaty*, Articles VI–IX; United Nations. (1972). *Liability Convention*.

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A deeper challenge lies in the jurisdictional ambiguity inherent in outer space governance. According to the Outer Space Treaty, outer space is res communis—a global commons not subject to national appropriation[16]. While this principle safeguards space from sovereignty claims, it also creates enforcement vacuums: no single entity or court has clear authority over debris-related disputes unless damage occurs, and the Liability Convention is triggered. This ambiguity undermines accountability, particularly in instances where the origin of debris is unclear or where damage results from cumulative, rather than singular, actions.

The increasing commercialization of space adds to the widening divide between utilization and protection. With the entrance of private actors such as Space-X, OneWeb, and Amazon's Project Kuiper for satellite deployment, orbital congestion has come to the fore. International space law remains state-centric and confers liability and regulatory obligations solely to nations[17]. States are supposed to be over the top of non-governmental activities; however, where private judges are concerned, the enforcement mechanisms on these private parties remain weak or non-existent, especially in States that lack national space legislation[18].

Yet another emerging yet pressing area is the lack of binding legal norms on space traffic management (STM). Thousands of satellites are currently operating in LEO, and so the danger of collision, interference, and miscommunication is rising. Yet, there does not exist a globally harmonized framework for collision avoidance, data sharing, and warning systems. Likewise, the question of debris remediation, i.e., active debris removal, or on-orbit servicing, remains hardly developed from a legal point of view. Unsettled major legal questions concern property, consent, salvage rights, and liability issues in the removal of defunct objects, and gaps in the legal system breed uncertainty and discourage solutions[19]. Lastly, there are no institutional infrastructures to monitor and adjudicate infringements of best practices or sustainability standards. Unlike environmental treaties, which rely upon treaty bodies or compliance committees, the space law regime does not have any standing authority to audit, inspect, or sanction non-compliant actors. Such an institutional weakness places the whole matter of orbital protection at the mercy of goodwill and unilateral compliance, which is insufficient in the face of escalating geopolitical and commercial competition in space.

In short, the present legal setting is drastically out of synchronization with technological

[16] Tronchetti, F. (2009). *The Exploitation of Natural Resources of the Moon and Other Celestial Bodies: A Proposal for a Legal Regime*. Brill, pp. 66–68.
[17] Outer Space Treaty, Article VI: "States shall bear international responsibility for national activities in outer space... whether carried on by governmental or non-governmental entities."
[18] Jakhu, R., Pelton, J. N., & Nyampong, Y. (2017). *Space Mining and Its Regulation*. Springer, pp. 110–112.
[19] Freeland, S. (2010). "Up, Up and … Back: The Emergence of Space Tourism and Its Impact on the International Law of Outer Space." *Chicago Journal of International Law*, 11(1), 10–25.

 [ISSN 2581-5369]

advancements and commercial realities in outer space. With the lack of binding international norms, clear jurisdictional clarity, and all-inclusive governance mechanisms, the international community is far from capable of tackling this ever-growing crisis of space debris. Filling in these gaps is, therefore, imperative for the twin concerns of safety and sustainability and to maintain the space as a shared global environment for future generations to come.

V. RECOMMENDATIONS

With space debris growing into a danger for the orbital environment, satellite infrastructure, and long-term space sustainability, the international community ought to embark on courageous, novel, and highly coordinated legal reforms. Some recommendations are laid out for strategizing a roadmap toward a strong and environmentally conscious outer space governance regime:

A. The global treaty for the protection of orbital environment

There is an absence of a binding international treaty solely oriented toward the regulation of space debris. Such a legislative silence is unacceptable and, thus, begs a prompt construction of a comprehensive multilateral treaty under the auspices of the United Nations or a dedicated international space environmental body responsible for matters pertaining to space environmental concerns. The definition of space debris must find its place in the list of legal terms. The treaty would impose obligations on states and private actors for debris mitigation and set out compliance mechanisms for enforcement. Also necessary would be the establishment of the principle of environmental justice, intergenerational equity, and sustainable development, modified appropriately for outer space.

B. Debris mitigation protocols legally binding

In that UNCOPUOS guidelines are seemingly valuable, their lack of binding nature does not allow them to become actually effective. The next step would have to be conversion of these guidelines into enforceable protocols with mandatory compliance standards. These protocols should include:

a) Safe end-of-life disposal of satellites,

b) Collision avoidance regimes,

c) Prohibition of deliberate ASAT tests,

d) Standard operators for debris-tracking and -reporting mechanisms.

 [ISSN 2581-5369]

C. Orbital environmental impact assessments (OEIAs)

The need for Orbital Environmental Impact Assessments (OEIAs) should be institutionalized as a precondition to space launches. Just as on Earth a project must assess environmental impacts, space-faring entities are obliged to assess potential orbital pollution from every launch, satellite operation, or constellation. OEIAs would help inculcate a preventive spirit of governance in the system, promote transparency, and enable regulators to screen proposals that are of higher risk. On the international front, OEIAs can provide the phase of review during which cooperation and confidence building can take place.

D. Encouraging active debris removal and responsible design

Apart from an approach based on regulation, countries and space agencies would do well to consider the carrot-and-stick approach to encourage sustainable behavior. Such rewards could involve tax breaks, priority in launches, or subsidized payments to private actors engaged in active debris removal (ADR). Technology transfer and joint missions for the use of less developed spacefaring nations may also be permitted. Spacecraft design requiring debris-resilience and passivation compliance may be part of licensing conditions.

This will, in turn, encourage the nascent yet potentially crucial area of space-cleaning technologies needed to tackle the accumulated orbital debris.

E. Integrating the space law discourse with environmental law discourse

The greater question should lie in embedding environmental protection into the body of space law, treating the orbital environment as an ecological realm demanding legal stewardship. In its present condition, space law must develop perhaps in those respects where climate change, ocean governance, or the law of the sea has developed-from sovereignty and liability to ecological duties. There should be some academic and institutional discourse of cross-disciplinary frameworks in this way that they may be able to shed environmental ethics, ecological economics, and international environmental law principles into the governance of space.

VI. Conclusion

For a very long time, space debris was a technical concern with little significance. Now, it has become an environmental and legal crisis. The freeflow of non-functional satellites, collision fragments, and operational waste through Earth's orbit; in other words, if the existence of debris in the orbit is not checked, they also pose a threat to present space missions and the future destiny that space shall exist as a common resource for humanity. Therefore, any

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danger considered formerly as operational and far-away has now become an ecological and governance challenge that needs to be faced by law scholars and policy experts alike, questioning economic and political international institutions.

Without strong legal intervention, outer space may well follow the same course as the oceans, the atmosphere, and the forests of the Earth: damaged by overuse, under-regulated, and polluting. The current framework of international law is insufficiently adapted to the peculiarity of orbital pollution. It lacks binding obligations, enforcement mechanisms, and institutional oversight. Soft law had its day, but now it is an issue of jurisdiction, aggravated by commercial interests asserting themselves in the regulatory vacuum. The situation is unsustainable and dangerous. Time is ticking. Our opportunity for preventive measures is quickly narrowing. It, therefore, necessitates action on the international stage for the purposes of swiftly preparing a multilateral, legally binding framework searching for orbital sustainability issues as proving injustice in the environment at least to engineering prudence. This framework must be inclusive, enforceable, and forward-looking—based on environmental principles, innovative to adapt to technological changes, and capable of regulating orbital commons increasingly populated. In this way, we ensure outer space remains a safe, accessible, and sustainable domain for all humans today and, in the coming years.

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 [ISSN 2581-5369]