Comparative planetology as a foundation for associating space law with solar geoengineering governance: stratospheric aerosol injection and variations of sulfur dioxide in Venus's atmosphere

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Abstract

Mankind often seeks solutions to climate change and environmental crises, but rarely considers the feasibility of outer space to overcome such critical issues. Among many solar geoengineering approaches is stratospheric aerosol injection (SAI) whose concept suggests artificial control of the global temperature by spreading tones of sulfur dioxide into Earth's stratosphere. Given that the classic 'technology control dilemma' represents the central problem of solar geoengineering governance, however, this paper adopts a Venus-Earth comparative planetology method by addressing volcanology and atmospheric circulation aspects. An international regulatory framework engaging space law in solar geoengineering governance is consequently presented, which classifies two separate legislations: (1) research-based legislation (comparative planetology and Earth science) and (2) non-research-based legislation (national and international governance, ethical issues, economic factors, military utilization). Further highlighting climate change issues, SAI manifests the Anthropocene and regards Earth's stratosphere as an "inner environment", while comparative planetology manifests the Anthropocosmos and regards space as an "outer environment". This polymorphous consideration of atmospheric and space elements identifies a new approach of climate change techniques. Human relations that concern both environments should examine how social scientists would regard these separate boundaries or perceive them as a mergence between the two major epochs.

Keywords: *space law; comparative planetology; solar geoengineering; legislation; climate change; stratospheric aerosol injection.*

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1. Introduction

Various contrasting perceptions have been developed, analyzed and expressed by scientists, as well as non-scientists, concerning the technical concepts and feasibility of various Solar Radiation Management (SRM) proposals, which seem to include every geographical location – atmospheric, terrestrial, and even space-based. In regard to SRM proposals whose immediate application is limited within the boundaries of Earth, however, space-based projects are often deemed as technically complex and burdensome, as well as extremely costly. The Royal Society in particular, suggested that the costs of setting in place such a space-based armada for the relatively short period that SRM geoengineering may be considered applicable (decades rather than centuries) would likely make it uncompetitive with other SRM approaches.[5] Alternatively, stratospheric aerosol injection (SAI) represents one of the most promising atmospheric forms of SRM proposals in the scientific community. The idea of possible artificial control of the global temperature by spreading tones of sulfur dioxide into the Earth's stratosphere may not be as disputable as it currently seems, despite being quite controversial in comparison to, for instance, space-based solar power stations that are believed to potentially represent the new frontier. Prominent universities across the globe have seriously begun to develop research programs, such as Harvard's Solar Geoengineering Research Program[6], in an attempt to successfully address this alternative from multiple aspects, including science, technology and public policy and governance. This does not indicate that SAI represents the "perfect" temporary solution for climate change. On the contrary, there are a plethora of reasons why certain scientists and non-scientists manifest a strong reluctance towards the technological concept of SAI and, therefore, solar geoengineering research programs may not necessarily convince scientists, legislators, politicians and even ordinary civilians regarding its ultimate efficiency. Before examining how a research program might be established, much can be learned from reviewing the deep concerns that have held back previous efforts: uncertainty, slippery slope, messing with nature, governability, and moral hazard.[7] This rational observation may contribute for SAI to be looked upon as flawed enough to not be applicable in the near future. And even though every technology cannot be entirely immune to risks, the decision of not considering SAI into practical application could develop an even greater risk for our planet. The central purpose of research is to reduce uncertainty; so although there is much that we don't know about solar geoengineering, that cannot stand alone as an argument against research.[8] Consequently, this paper adopts the method of comparative planetology, where it argues that one of the fundamental issues concerning the

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[5] The Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty*, Science Policy, London, 2009, p. 50.

[6] *Harvard's Solar Geoengineering Research Program*, Harvard University, n.d., available at https:// geoengineering.environment. harvard.edu/ (last accessed May 15, 2022).

[7] David Keith, *Toward a Responsible Solar Geoengineering Research Program*, "Issues in Science and Technology", 2017, Vol. 33(3), p. 72.

[8] *Ibid*, p. 72.

technological concept of SAI is that it does not maximally include the use of outer space, but rather only mentions it as the ultimate environment of where previously released particles in the stratosphere, would reflect sunlight towards outer space. As both space-based SRM proposals and SAI currently contain many imperfections and inconvenient characteristics, comparative planetology might contribute towards the merge of space-based and atmospheric SRM proposals, at least from a derivative perspective. With respect to SAI and the climatic effects of aerosols, an important and complex problem linking chemical, dynamical, and radiative effects involves the characteristics of sulphur acid hazes. On Earth, a thin continuous haze of sulphuric acid droplets resides in the stratosphere, whereas thicker but more localized hazes form in the troposphere. The most extensive sulphuric acid haze known in the solar system is found in the atmosphere of Venus. This cloud is both thick and continuous, and resides about 60 km above Venus' surface. Comparison of the Earth with Venus can contribute to our understanding of the haze phenomenon, and improve our understanding of its climatic importance.[9] This proposition offers a changing perspective where we ask ourselves if the knowledge obtained from studies of other planets' atmospheres can help scientists and legislators improve our methods and technologies for climate change, as well as other environmental crises and issues. The method of comparative planetology would not only eliminate the uncertainties that the scientific community is presently facing, but also enrich the scientific background development in regards to SAI. Another benefit of fundamental importance is the emergence of international environmental governance defined by the application of comparative planetology, which is not exactly a notorious or applicative notion in international legislation. This would lead towards a prospective International Regulatory Framework for Solar Geonegineering in the future which would further guarantee and manifest the efficiency and productivity of SAI as a promising technology to address climate change.

Space is a new destination that is open to all mankind. According to space treaties, outer space should be used in the interest of all nations on equal and fair conditions. Fast commercialization and opening new space markets to different international entities should be accomplished in concert with the implementation of professional management of space activities[10].

2. Stratospheric aerosol injection and the variations of sulfur dioxide of Venus's atmosphere: methods of comparative planetology

Venus is often named as Earth's twin because both share a similar size, surface composition and have an atmosphere with a complex weather system[11], as

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[9] Ralph Kahn, *Comparative Planetology and the Atmosphere of Earth: A Report to the Solar System Exploration Division, National Aeronautics and Space Administration*, Jet Propulsion Laboratory, La Cañada Flintridge, 1989, p. 17.

[10] See Małgorzata Polkowska, *Space Tourism Challenges*, „Review of European and Comparative Law", 2021, vol. 45(2), p. 178.

[11] *Venus Compared with the Earth*, Ajax, n.d., available at http://www.ajax.ehu.es/VEX/Venus.Earth/Venus.Earth.html (last accessed May 15, 2022).

well as the fact that they were both formed around the same time and in the same region in the solar system. As a result, Venus represents an extremely convenient celestial body to be subjected to comparative planetology for the purposes of this paper, where naturally occurring atmospheric effects on Venus, including volcanism, clouds and haze layers, will serve as important environmental factors. The primary focus is respectively placed upon the amount and origin of sulfur dioxide in both Earth's and Venus's atmospheres in order to attempt to appropriately compare it to the predicted efficiency of the SAI technique which could cool the planet in a similar way to a large volcanic eruption. When a volcano erupts, it sends an ash cloud high into the atmosphere. The sulfur dioxide released in the plume combines with water to form sulfuric acid aerosols, which are able to reflect incoming sunlight. Sulfur dioxide is often proposed as the most likely candidate for aerosol release.[12] Though a stratospheric aerosol injection experiment hasn't been conducted, scientists do have an idea of what happens when tiny particles are spewed into the upper atmosphere thanks to volcanic eruptions. When Mt. Pinatubo in the Philippines erupted in 1991, the roughly 20 million tons of sulfur dioxide it tossed 20 miles up cooled global temperatures by 0.6 degrees Celsius for 15 months. Beyond the Pinatubo eruption, we have few data points that reveal how sulfur in the stratosphere would affect the planet.[13] But these natural processes are uncontrolled and in many cases cause very big adverse environmental changes themselves. Of course, the particulates and gases coming out of a volcano are not the ones we would choose in solar geoengineering.[14] While sulfur dioxide in Earth's atmosphere mainly originates from anthropogenic emissions and released by volcanic eruptions, it is of extreme relevance to properly understand the variations in the amount and origin of sulfur dioxide in Venus's atmosphere, and more importantly, the environmental factors that contribute for those variations. Venus's atmosphere is completely covered by thick clouds, that is, a cloud layer of 50 to 70 km altitude, which is composed of sulfur dioxide particles. Although the planet has often been visited by multiple spacecraft over the years, using ESA's Venus Express spacecraft, in orbit around Venus since 2006, and its on-board SPICAV instrument, the researchers discovered the presence of gaseous sulfur dioxide high up in the atmosphere, at an altitude of 90-110 kilometers. The researchers believe that the sulfur dioxide derives from the sulphuric acid mist in the upper atmosphere of Venus. On the day side of Venus, the temperature increases with altitude above 90 kilometers which causes the sulphuric acid to evaporate. It then decomposes under the effect of solar

[12] Daisy Dunne, *Explainer: Six Ideas to Limit Global Warming with Solar Geoenginering*, Carbon Brief, 2018, available at https://www.carbonbrief.org/explainer-six-ideas-to-limit-global-warming-with-solar-geoengineering/ (last accessed May 15, 2022).

[13] Rachel Kaufman, *The Risks, Rewards and Possible Ramifications of Geoengineering Earth's Climate*, Smithsonian Magazine, 2019, available at https://www.smithsonianmag.com/science-nature/risks-rewards-possible-ramifications-geoengineering-earths-climate-180971666/ (last accessed May 15, 2022).

[14] James Conca, *Why Solar Geoengineering May Be Our Only Hope to Reverse Global Warming*, Forbes, 2019, available at https://www.forbes.com/sites/jamesconca/2019/09/10/solar-geoengineering-we-better-do-it-or-well-burn/?sh=10b4318918ad (last accessed on May 15, 2022).

radiation, producing sulfur dioxide.[15] Emanuel Marcq and accompanied researchers in the 2012 research paper titled *"Variations of sulphur dioxide at the cloud top of Venus's dynamic atmosphere"*[16] have reported that the sulphur dioxide column density above Venus's clouds decreased by an order of magnitude between 2007 and 2012 using ultraviolet spectrometer data from the SPICAV instrument onboard the Venus Express spacecraft. This decline is similar to observations during the 1980s. They have also reported strong latitudinal and temporal variability in sulphur dioxide column density that is consistent with supply fluctuations from the lower atmosphere. Having this acknowledgement in consideration, the authors of the paper in Nature Geoscience suggest two possible explanations: periods of active volcanism, or long-term variability in the general circulation of the atmosphere.[17] As contrasting environmental factors in terms of sources or origin of the amount of sulfur dioxide in Venus's atmosphere, both suggestions must be analyzed separately in order to make a comparison with identical environmental occurrences on Earth and whether the SAI technological concept would, consequently, be applicable enough. In continuation, two individual and respective analyses will be displayed with the purpose of manifesting the method of comparative planetology.

2.1 Venus-Earth volcanology

The discovery of episodic sulfur dioxide injections in Venus's atmosphere might be the result of recent volcanic eruptions occurring on Venus. The fact that Venus's surface predominantly contains volcanoes and volcanic features indicates towards a strong presumption that volcanic activity might be responsible for the significant increase of sulfur dioxide in the upper atmosphere. However, even this presumption could be debatable in terms of resent volcanic activity on Venus. The evidence was tantalizing, but incomplete. *"The data that are currently available for Venus cannot unequivocally provide the smoking gun"*, said Tracy Gregg, a geologist at the University at Buffalo.[18] Most of the sulphur dioxide on Venus is hidden below the planet's dense upper cloud deck, because the gas is readily destroyed by sunlight. That means any sulphur dioxide detected in Venus' upper atmosphere above the cloud deck must have been recently supplied from below. Nevertheless, Dr

[15] The French National Centre for Scientific Research (CNRS), *Sulfur dioxide in Venus' atmosphere could be the key to fighting global warming on Earth*, Phys, 2010, available at https://phys.org/news/2010-11-sulfur-dioxide-venus-atmosphere-key.html (last accessed May 15, 2022).

[16] Emmanuel Marcq, Jean-Loup Bertaux, Franck Montmessin and Denis Belyaev, *Variations of sulfur dioxide at the top cloud of Venus's dynamic atmosphere*, "Nature Geoscience", 2013, Vol.6. The document is available online at http://www.issibern.ch/ teams/venusso2/multimedia/ pdf/Marcq_13.pdf (last accessed May 15, 2022).

[17] Emmanuel Marcq, Lean-Loup Bertaux, and Håkan Svedhem, *A New Episode of Active Volcanism on Venus?*, European Space Agency (ESA), 2012, available at https://sci.esa.int/web/venus-express/-/51185-a-new-episode-of-active-volcanism-on-venus (last accessed May 15, 2022).

[18] Shannon Hall, *Volcanoes on Venus Might Still Be Smoking*, New York Times, 2020, available at https://www.nytimes.com/2020/01/09/science/venus-volcanoes-active.html (last accessed May 15, 2022).

Jean-Loup Bertaux speculated that: *"A volcanic eruption could act like a piston to blast sulphur dioxide up to these levels, but peculiarities in the circulation of the planet that we don't yet fully understand could also mix the gas to reproduce the same result."*[19] Contrastingly enough, Earth's volcanic activity in relation to sulfur dioxide, the greatest volcanic impact upon the earth's short term weather patterns is caused by sulfur dioxide gas. In the cold lower atmosphere, it is converted to sulfuric acid by the sun's rays reacting with stratospheric water vapor to form sulfuric acid aerosol layers. The aerosol remains in suspension long after solid ash particles have fallen to earth and forms a layer of sulfuric acid droplets between 15 to 25 kilometers up. Fine ash particles from an eruption column fall out too quickly to significantly cool the atmosphere over an extended period of time, no matter how large the eruption. Sulfur aerosols last many years, and several historic eruptions show a good correlation of sulfur dioxide layers in the atmosphere with a decrease in average temperature decrease of subsequent years. The close correlation was first established after the 1963 eruption of Agung volcano in Indonesia when it was found that sulfur dioxide reached the stratosphere and stayed as a sulfuric acid aerosol. Without replenishment, the sulfuric acid aerosol layer around the earth is gradually depleted, but it is renewed by each eruption rich in sulfur dioxide. This was confirmed by data collected after the eruptions of El Chichon, Mexico (1982) and Pinatubo, Philippines (1991), both of which were high-sulfur compound carriers like Agung, Indonesia.[20]

2.2 Venus-Earth atmospheric circulation

In the eventual case of absence of active volcanism on Venus, the second suggested possibility, which simultaneously serves as an alternative explanation for the increased sulfur dioxide in Venus's atmosphere is the result of long-period oscillations of the general atmospheric circulation. Venus has a 'super-rotating' atmosphere that whips around the planet in just four Earth-days, much faster than the 243 days the planet takes to complete one rotation about its axis. Such rapid atmospheric circulation spreads the sulphur dioxide around, making it difficult to isolate any individual points of origin for the gas.[21] Still, it must be noted that Venus's atmospheric circulation cannot be fully understood just yet, however, that does not necessarily prevent certain methods of comparative planetology, even if they are primarily of theoretical nature. Atmospheric circulation, in relation to climate changes, should be regarded as a relevant factor since it represents the large-scale movement of air and is the predominant reason why heat is appropriately distributed on Earth's surface. Compared to Venus's atmospheric circulation, Earth is also considered as a superrotator – the atmosphere turns about the planet faster than the

[19] Damien Gayle, *We already know she's hot stuff: But could volcanoes on Venus be spewing sulphur dioxide into its atmosphere?*, Daily Mail, 2012, available at https://www.dailymail.co.uk/sciencetech/article-2242164/Could-volcanoes-Venus-spewing-sulphur-dioxide-atmosphere.html (last accessed May 15, 2022).

[20] Richard V. Fisher, Grant Heiken and Jeffrey B. Hulen, *Volcanoes: Crucibles of Change*, Princeton University Press, Princeton, 1997, p.165.

[21] Damien Gayle, *op. cit.*, 2012.

surface beneath. However, our current knowledge indicates that while planetary atmospheres share physical processes, they exhibit diverse characteristics.[22] As a finishing interpretation of the above analyzed comparative environmental factors between Venus and Earth, it is necessary to "reform" the seemingly various proposed possibilities. In other words, both volcanology and atmospheric circulation are regarded as separate suggestions in regards to the question of what exactly is the source of increased sulfur dioxide in Venus's atmosphere. A particular method of comparative planetology may not necessarily continue to regard them as environmental *"factors"*, but rather as environmental *"advantages"* due to Earth's far less extreme environmental and atmospheric conditions compared to Venus, which allows for SAI technology to appear significantly more supportable and effective on our planet. This concept is especially important to comprehend, since the rather pessimistic question of whether Venus is a mirror that reflects how the Earth will be if global warming continues its current speed, is often asked: *"Venus will help us understand what happens when the greenhouse effect is really extreme. However, it's not a good example of what will happen to Earth due to human activities. Life on Earth would disappear due to the extreme temperatures much more before reaching even half of the concentrations of carbon dioxide on Venus."* – says Hakan Svedhem, Project Scientist for ESA's mission Venus Express.[23]

The relationship between the similarities and differences of volcanology and atmospheric circulation manifested separately on both planets should be properly distributed between their scientific and technological treatment, all while maintaining an interdependent connection from a legal and technical aspect. Namely, while unanswered questions concerning volcanology and atmospheric circulation in Venus's atmosphere should be regarded as reasons for their further scientific research, the apparent notion of regarding volcanology and atmospheric circulation as potential advantage for the practical application of SAI only tends to emphasize its technological treatment, which simultaneously leads us to the next point.

3. Comparative planetology: the groundwork for SAI governance and an international regulatory framework for solar geoengineering

The potential opportunities, benefits, harms, and risks of geoengineering the climate will almost certainly create incentives to manipulate geoengineering choices and the stakes will be enormous.[24] One of those incentives is the governance of solar geonegineering, including SAI. However, there are many flaws and limitations in the attempt to establish the notion of governance and policy based on scientific and

[22] Xun Zhu, *Dynamics in Planetary Atmospheric Physics: Comparative Studies of Equatorial Superrotation for Venus, Titan and Earth*, "John Hopkins APL Technical Digest", 2005, Vol. 26(2), p. 165.

[23] *Greenhouse effects…also on other planets*, European Space Agency (ESA), 2003, available at https://www.esa.int/Science_Exploration/Space_Science/Venus_Express/Greenhouse_effects_also_on_other_planets (last accessed May 15, 2022).

[24] Jane S.C. Long and Dane Scott, *Vested Interests and Geoengineering Research*, "Issues in Science and Technology", 2013, Vol. 29(3), p. 45.

technological grounds, as well as an international regulatory framework. Governance is the toughest challenge for geoengineering. A global research program should therefore be coupled with greatly expanded international discussion about these technologies and their governance.[25] Technical, legal, ethical, economic and other concerns need to be balanced carefully in a policy and governance framework which is international in scope and remains flexible in light of fresh evidence. The central problem for the governance of geoengineering is that while potential problems can be identified with all geoengineering technologies, these can only be resolved through research, development and demonstration. This is the classic 'technology control dilemma',[26] which could be addressed by this paper's particular method of comparative planetology to significantly contribute the necessity of SAI governance, as well as the formation of solar geoengineering international regulatory framework, respectively. Even so, the process of this engagement requires an appropriate legislative division. From a legal standpoint, this may seem difficult to achieve, which is understandable given that so far it cannot be formally or practically confirmed that comparative planetology and its methods have been directly associated with international environmental law, or with any legislation in general. Therefore, the presentation of comparative planetology as a solid groundwork for SAI Governance, as well as an International Regulatory Framework for Solar Geoengineering should manifest the already mentioned division of two separate legislations:

- **Research-based legislation:**
  - *Comparative planetology;*
  - *Earth science;*
- **Non-research-based legislation:**
  - *International governance;*
  - *National governance;*
  - *Ethical issues;*
  - *Economic factors;*
  - *Military utilization regulation;*
  - *Public utilization regulation.*

Research-based legislation, indicative by the term itself, is specifically dependent on research conducting resulting in scientific understandings. However, it is limited, from a legal perspective, in terms by which it specifically implies to scientific research conducted within the boundaries of our planet - Earth science, with the purpose of discovering how SAI technology can be improved in regards to Earth's stratosphere. Therefore, contemporary legislation and governance formally acknowledge the necessity to regulate SAI technological development under the notion of *"Governing of Geoengineering Research and Development"*. That being said, methods of comparative planetology are not specifically considered within this

[25] David Keith, *Let's Talk About Geoengineering*, Harvard University, 2019, available at https://keith.seas.harvard.edu/news/let%E2% 80%99s-talk-about-geoengineering (last accessed May 15, 2022).

[26] The Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty*, Science Policy, London, 2009, p. 37.

legislation. One may say that comparative planetology research should simply be considered within Earth-based research governance. While it was previously discussed how the environmental occurrences of volcanic activity and atmospheric circulation should be separately regarded as *factors* on Venus, due to unanswered questions of scientific relevance for the source of sulfur dioxide in Venus's atmosphere, and as *advantages* on Earth, its far less extreme environmental and atmospheric conditions allows for SAI technology to appear more realistic and applicable in the near future. Moreover, another important question arises along with the potential involvement of comparative planetology regarding SAI governance and policy: *How does space law fit in this governance?* This argument urges the necessary involvement of space law in comparative planetology governance, as well as its absence in Earth-based research governance. This legal differentiation is derived from the method of conduct and the method of research, where SAI technology is strictly developed and would be conducted in Earth's stratosphere. Therefore, it is logical for national and / or international air law to apply. Since the aerosols are transported to the stratosphere by an airplane, it is suggested that the supposed airplane would fly among that altitude of the stratosphere where the air would not be so thin for balloons or other objects characteristic to operate within near-space (the mesosphere), as the question of delimitation still remains debatable from a legal perspective. Both national and international law are mentioned and taken into consideration within this context due to the fact that so far, we don't have any national controls, let alone global controls. Today, someone could launch a fleet of airplanes to spray aerosols or other substances into the upper atmosphere, and it arguably would not violate any laws.[27] In addition, even though the status of the airplane fleet in question is not officially determined, it would be of great relevance to further determine their civil, commercial or military identification, as it could make a difference in regards to air law regulation. Nevertheless, the distinction between air law and space law is quite clear in this scenario, as there are no indications that it is necessary for space law to be included in Earth-based research governance, as well as the practical application of SAI technology in the future, as it has no direct contact with outer space, except for the intention of the sprayed particles to reflect sunlight back to outer space, which does not involve any manned on unmanned objects being launched above Earth's stratosphere and thus creating a justifiable activity to be properly regulated. On the other hand, research-based comparative planetology governance would derive its sources from unmanned space exploration mission, as a manifestation of physical exploration. In compliance with researching SAI technology, methods of comparative planetology are applicable towards Venus as a target of exploration, due to the confirmed fundaments of environmental comparison of surface and atmospheric characteristics. As one of the fundamental parameters of space law, unmanned space explorations are subjected to many regulation issues. For instance, Jacek Machowski in his paper "*Legal Status of*

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[27] Sarah Fecht, *We Need Laws on Geoengineering, ASAP*, State of the Planet, 2018, available at https://news.climate.columbia.edu/ 2018/03/20/geoengineering-climate-law-book/ (last accessed May 15, 2022).

Unmanned Space Vehicles"[28] has discussed about the specific legal problems linked with the launching of unmanned space vehicles:

1. Permissibility of launching unmanned space vehicles;
2. The problem of control of unmanned space vehicles;
3. The legal analogies for unmanned space vehicles;
4. The problem of ownership of the unmanned space vehicle;
5. The problem of liability for injury or damage from unmanned space vehicles.

Simultaneously enough, unmanned spacecraft for space exploration, such as ESA's Venus Express spacecraft, are expected to undergo various legal requirements proposed by space law for the advanced scientific study of the variations of sulfur dioxide of Venus's atmosphere and its further comparison to SAI technological development. Of course, space agencies engaging in space exploration missions on Venus should take into consideration every aspect of the pre-launch and launch of their spacecraft. In other words, comparative planetology represents the key element and foundation for the involvement of space law and governance in regards to SAI technology and possibly other space-based SRM proposals. Space exploration can, therefore, be applicable for the second-mentioned classification of research-based legislation – comparative planetology. Regardless, non-research based legislation, being recognized as another legal classification in relation to SAI, is strongly interdependent with the first-mentioned legislation. This relation and effect upon one another further dictates the hierarchy between both proposed legislations. Namely, they are to be regarded as primary and secondary, in terms of their practical application. Research-based legislation should enjoy the role of being considered as a primary legislation, along with comparative planetology and Earth science as methods of research, respectively. Consequentially, non-research-based legislation should be considered as a secondary legislation. The reasoning behind this hierarchy between both legislations is the notion of moratorium, being recognized as a delay or suspension of an activity to be carried out. In relation to SAI and solar geoengineering in general, since international legislators and the scientific community are currently dealing with multiple issues that currently unable the practical application of SAI, the repercussion of the further research of solar geoengineering is recognized and respected by nations. This repercussion can be simultaneously applicable to comparative planetology research, since research-based legislation should not differentiate comparative planetology from Earth science as a method by which SAI can be further improved and developed. Scholars, advocates and other frequently suggest that outdoor solar geoengineering activities that surpass certain scales not take place until certain conditions have been met. Daniel Bodansky states that moratoria 'have the attraction of simplicity. They create bright-line rules, and thus avoid the need for complex, ongoing decision-making, which may be beyond the institutional capacity of the international community,

[28] Jacek Machowski, *Legal Status of Unmanned Vehicles*, U.S. Congress Reports and Documents Volume 33, Washington, 1961, p.1204.

particularly in cases of significant uncertainty.[29] Similarly enough, uncertainty is one of the most prominent concerns in regards to SAI and SRM proposals, generally speaking. In relation to comparative planetology as a classification of research-based governance, uncertainty is manifested by our speculations about the source of variations of sulfur dioxide in Venus's atmosphere, which should simultaneously help scientists understand SAI in order to apply it in the near future. In continuation, as separate environmental factors on Venus, volcanology and atmospheric circulation are beneficial for conducting solar geoengineering on Earth. However, apart from uncertainty as an identified concern, the notion of moratorium additionally links comparative planetology with another social challenge – slippery slope. If the slope from research to deployment is slippery because research reveals that solar geoengineering works better and with less risk that we now expect, that slipperiness is not itself an argument against research. The basis for concern about slippery slopes is the socio-technical lock-in that arises when technologies coevolve interdependencies with other technologies and when they develop political constituencies that encourage continued use even against the public interest.[30] Consequently, methods of comparative planetology focused to determine the sources of the variations of sulfur dioxide in Venus's atmosphere and simultaneously balance that knowledge in regards to SAI development, would not represent a valid reason to support the concept of SAI and its practical application in general. On the contrary, the main determinants for the slipperiness from comparative planetology research to SAI application would be its role in terms of the development of a destructive utilization of SAI in terms of its termination of identification as a public good, military application and as a subject of military misuse. Specifically on SAI for military application, in 1977, an international Convention was ratified by the UN General Assembly which banned 'military and other hostile use of environmental modification techniques having widespread, long-lasting or severe effects'. According to the Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques: *the term "environmental modification techniques" refers to any technique for changing – through the deliberate manipulation of natural processes – the dynamics, composition or structure of the Earth, including its biota, lithosphere, hydrosphere and atmosphere, or of outer space.* (Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, United Nations, Geneva: 18 May 1977)[31].

Even though the usage of climate modification for military purposes is still considered a scientific taboo, in relation to SAI, its seemingly straightforward

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[29] Jesse L. Reynolds, *Solar geoengineering to reduce climate change: a review of governance proposals*, "Proceedings of the Royal Society of Mathematical, Physical and Engineering Sciences", 2019, 475, p. 14.

[30] David Keith, *op. cit.*, 2017, p. 73.

[31] Michael Chossudovsky, *The Ultimate Weapon of Mass Destruction: "Owning the Weather" for Military Use*, Global Research, 2018, available at https://www.globalresearch.ca/the-ultimate-weapon-of-mass-destruction-owning-the-weather-for-military-use-2/5306386?utm_campaign=magnet&utm_source=article_page&utm_medium=related_articles (last accessed May 16, 2022).

conduct and inexpensive application in the future might be the slipperiness for the fear of military misuse. In other words, the application of SAI as course of environmental action could yet inevitably lead towards its weaponization - the destructive consequence whose emergence was, in any case, intended by the public. The representation of SAI as beneficial to the well being of the public could be immensely challenged by ethical issues. In addition to this statement, some scientists have raised concerns that, if aerosols were used to address global warming, the world could be left at risk of a "termination shock". That is, if aerosols were released and then suddenly stopped – as a result of political disagreement or a terrorist attack, for example – global temperatures could rapidly rebound.[32] In this connotation, a research article published in Earth's Future, argues that this risk has been "significantly overestimated". There are numerous ways to prevent termination shock occurring, the researchers say, and also to ensure that an SRM programme is resilient to physical, political or economic interruptions in the first place. The study specifically focusing on SAI, argues that there are two main reasons why an SRM program would be terminated early, the paper suggests: because someone forced it to stop, or because people made a decision to stop it.[33]

Policy-makers should address SRM proposals such as SAI, in a sense that it would manifest global consent and to ensure for limited possibilities of legal loopholes in multilateral regulations on solar geoengineering which would further contribute for any irrational or unreasonable behavior in regards to decision makers. In other words, an international regulatory framework for solar geoengineering should manifest the notion of *Spaceship Earth* – the universal perception with the aim to encouraging decision makers to act as a harmonious crew working toward the greater good, and in this case, that greater good represents artificial climate modification for the reducing of global warming and other serious environmental crises.

4. Stratospheric aerosol injection research development: *anthropocenic* vs. *anthropocosmic* approach

Highlighting climate change issues, the environmental concept of the *Anthropocene* is currently considered in a scientific context, although informally – noting and pertaining to a proposed epoch of the Quarternary Period, occurring in the present time, since mid-20th century, when human activity began to effect significant environmental consequences, specifically on ecosystems and climate.[34] From a geopolitical standpoint, the Anthropocene often represents the connection

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[32] Daisy Dunne, *Explainer: Six Ideas to Limit Global Warming with Solar Geoengineering*, Carbon Brief, 2018, available at https://www.carbonbrief.org/explainer-six-ideas-to-limit-global-warming-with-solar-geoengineering/ (last accessed May 15, 2022).

[33] Robert McSweeney, *Solar geoengineering: Risk of 'termination shock' overplayed, study says*, Carbon Brief, 2018, available at https://www.carbonbrief.org/solar-geoengineering-risk-termination-shock-overplayed-study/ (last accessed May 16, 2022).

[34] *Anthropocene*, Dictionary, n.d., available at https://www.dictionary.com/browse/anthropocene (last accessed May 16, 2022).

between the natural world and international relations, often of a political background, and based on the environmental scale, the Anthropocene serves as a key for sovereign states around the world to realize the significance of climate change and other environmental crises. Unfavorable and harmful transformations that are occurring today trigger the legal consequence of responsibility of one or multiple sovereign states.[35] The Anthropocene, the new geological age we are living in, suggests that while technology is crucial to human changes it is also part of the overall transformation of the biosphere – the context for humanity that we actively resemble, often with disastrous consequences for other species and their habitats. All of this suggests that we need to add a specifically geophysical understanding to the operations of power, linking physical transformations of context to into our understandings of power, prestige and the search for security of various types. National and international policies of natural and geographical position are manifested through climate change and other serious environmental issues. In other words, they serve the role of factors for guidelines regarding the structuring of effective policies that would enable states to study the significance and advantages of physical geographical space. The increasing technological and scientific developments, therefore, reflect the need of an appropriate approach of a social scientific background. Understandings of governing forces should not be perceived as a tool for domination of a particular geographical area or the world itself in general. However, technologies and scientific methods for the reducing effects of climate change and environmental issues, in an indirect manner, successfully manage to manifest the importance and necessity for control and possession in front of the overall international community. The study and explanation of these technologies and methods are additionally assisted by the notion of conceptualization and it is of great importance to grasp the essential elements of their features, characteristics and implications. Failure to comprehend the relevance of shaping the environmental future of planet Earth and beyond by international policies and geopolitical decisions could only result in further environmental and climate damages with far less chances of applying an appropriate and effective solution. SAI is appropriately regarded as an atmospheric SRM proposal and perceived to manifest the concept of the Anthropocene – the global environment primarily being shaped by humanity. And while its Earth science research-based method simultaneously manifests the Anthropocene effect, one may ask about its space-related aspect, which only includes outer space in an indirect context - a wide range of types of particles could be released into the stratosphere with the objective of scattering sunlight back to space.[36] This being said, the conducting of SAI based is predominantly perceived as an "inner environment". However, this could only apply upon Earth science-based research. The rather limited element of outer space in regards to SAI as the most discussed form of SRM tends to essentially modify the social scientific approach. Namely, the Anthropocene concerns with global

[35] Albert J. Bergesen and Christian Suter, *The Return of Geopolitics*, LIT Verlag, Münster, 2018, p. 164.
[36] The Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty*, Science Policy, London, 2009, p. 29.

environments have, in practice, delineated inner and outer environments, where the "outer" environments consist of the places beyond the atmosphere and beneath the lithosphere. This brackets what tends to count as the human environment to the space between the surface of the Earth and the limits of our atmosphere.[37] With that said, it is of great importance to be introduced to the notion of the *Anthropocosmos*: the epoch during which human activity is considered to be a significant influence on the balance, beauty, and ecology of the entire universe.[38] The use of outer space against climate change and environmental crises reflects upon a proto-Anthropocene planetary environment. At the same time, this can be achieved by comparative planetology methods in the development and better understanding of SAI. Being separately regarded, but still having relations to SAI, creates an environmental division in both science and law. From a geographical standpoint, the technological steps of SAI can be perceived from an "inner" environment (releasing particles into the stratosphere), as well as an "outer" environment (methods of comparative planetology). In regards to the global awareness of how human activity damages the environment, SAI does not necessarily reflect obstructive consequences for both the Anthropocene and Anthropocosmos periods, meaning that their immediate effects might contrast one another. Simply put, they are simultaneously dependent and independent. This polymorphous consideration of both atmospheric and outer space elements identifies with the formation of a new approach of climate change techniques. Human relations that concern both environments should attempt to examine how social scientists would regard these separate boundaries or perceive them as a mergence between the two major epochs.

5. Conclusions

The use of outer space from both scientific and legal standpoints is immensely beneficial for the contemporary SAI technology, given that although SAI cannot be entirely immune to a risk, it does not exclude its possibilities to be improved by research-based methodology. The method of Earth-Venus comparative planetology in aspects of volcanology and atmospheric circulation simultaneously benefits the advanced development of SAI, as well as the constructive engagement of space law in solar geoengineering governance. One of the main reasons why comparative planetology should be considered as a significant element of governance, policy and international regulation, is to better understand the relation between law and science. By familiarizing and comparing identical environmental occurrences in our solar system, the global community manages to perceive climate change, global warming and other serious environmental crises from a different point of view. While the atmospheres of other planets, that being Venus in this particular case, the study of data concerning the variations of sulfur dioxide in Venus's upper atmosphere might be of great value, as it is believed to improve our understanding

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[37] Julie Michelle Klinger, *Environmental Geopolitics and Outer Space*, "Geopolitics", 2019, p. 9.

[38] Joi Ito, *Space Exploration and the Age of the Anthropocosmos*, Wired, 2019, available at https://www.wired.com/story/space-exploration-and-the-age-of-the-anthropocosmos/ (last accessed May 16, 2022).

of SAI improvement and development, and furthermore, its international legal governance. Simultaneously highlighting climate change issues, SAI manifests the Anthropocene and regards Earth's stratosphere as an "inner environment", while comparative planetology manifests the Anthropocosmos and regards space as an "outer environment". This polymorphous consideration of atmospheric and space elements identifies a new approach of climate change techniques. Human relations that concern both environments should examine how social scientists would regard these separate boundaries or perceive them as a mergence between the two major epochs.

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