The Growing Space Industry: Exploring Potential Consequences of Rocket Emissions and Space Debris

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While the space industry continues to grow, there are still various unknowns about the implications created because of it. This research explored the concept of space sustainability and the possible implications that current launches could have in the future. It first delved into a literature review that focused on two main concerns: rocket emissions and space debris. There was a discussion on the problems that the current state of the space industry can pose and what solutions there may be to help fix this industry. The paper went into an analysis of data that had been gathered from various databases and other sources. The paper described the threat the current space industry creates for the future. Finally, more responsible and sustainable options are shown that can effectively be used for the future.

Introduction

Space has always been an intriguing and mysterious subject for humanity. The vastness of the universe and the countless celestial bodies that exist within it have sparked the curiosity of scientists and astronomers alike for generations. Space exploration began on October 4, 1957, when the Union of Soviet Socialist Republics launched Sputnik, the first artificial satellite to orbit the Earth[1]. Fast forward to the year 2021, which was a turning point in the spaceflight industry. Companies such as Virgin Galactic and Blue Origin began to offer space tourists tickets for suborbital spaceflight[2]. On top of that, SpaceX launched a record number of times and the National Aeronautics and Space Administration (NASA) awarded contracts for new private space station concepts[2]. However, while the rapid growth of the space industry will help us to learn more about the beyond, one problem arises. The growth of the space industry creates new business opportunities and ways to monitor the environment and human activities, but this leads to concerns with sustainability in space and on Earth[3]. Over 27,000 pieces of orbital debris are around Earth right now, and the fuels used in rockets can harm the environment and atmosphere[4,5]. While learning more about space will be monumental for the future, the lack of knowledge about the topic is also a great concern. In this paper, the main concern will be tackling the topic of space sustainability by focusing on two topics, space debris and rocket emissions. The following question guides the research to develop this paper: To what extent have space launches contributed to the worsening of space sustainability? Answering this question is important because it will provide insight into a problem that could become much worse. Knowing more about the nature of these problems is critical to attaining space sustainability. Sharing information about orbital space debris and rocket fuel emissions can help prevent these problems from happening and can help to create solutions to solve these problems.

Literature Review

With the rapidly growing space industry, there are a host of problems that can impact its future. However, rocket emissions and space debris pose some of the biggest threats to this ever-growing space industry[2,6,7]There are various concerns regarding the impacts of emissions on ozone and the environment and the threat of an exponentially growing space debris population. With the recent commercialization of this industry, it is important to look at how these launches affect the atmosphere and how a drastic increase in launches will impact the future.

Rocket Emissions

Rocket emissions have recently been recognized as a serious problem for space sustainability that deserves serious attention. In January 2020, J.A. Dallas et al. created a review discovering the environmental impacts of rocket emissions[6]. His team reviewed comprehensive literature, data, and technical reports provided by NASA and other sources to determine various effects that the most used rocket propellants had. His team covered five major effects: ozone depletion, mesospheric cloud formation, climate change, ecosystem toxicity, and human toxicity. J.A. Dallas's review inspired further research to be conducted on the impact of rocket emissions on the environment. Sirieys et al. review the rapidly growing space industry and how that will further exacerbate the threat that rocket emissions pose on the environment[2]. When first diving into the literature review, Dallas states that while studying the rocket's exhaust plume in real-time is more effective, using the global atmospheric has been more commonly used due to its ease[6]. This already displays a large weakness in the space industry, a lack of concern on the issue. Newer companies that are trying to capitalize on the commercialization of the space industry work to create the most profitable solution without concern for environmental impacts. What this creates is a rat race with many companies wanting to succeed in the commercial space industry. The more launches a company has, the greater its chances are of creating a successful rocket from which it can make large profits. This leads to a disregard for environmental impacts and a push to launch rockets in bulk. Sirieys and his team state that the overall number of rocket launches has grown 54% since 2001 due to commercial space industries[2]. The most common rocket fuels that are used today come in a solid form. However, the solid rocket fuels that are used are extremely dangerous to the environment and atmosphere[2,6]. The most common solid fuel that is used today is Ammonium Perchlorate[2,6]. This fuel has been used since the early stages of the rocket industry due to its relatively easy ability to store, high propellant density, high thrust, and relative ease of engineering an engine around it[6]. However, the launch effects that it has are extremely averse to the environment and atmosphere[2,6]. The most harmful emissions that come from Ammonium Perchlorate are chlorine and alumina[6]. Chlorine is an element that can disrupt the ozone cycle completely and alumina will act as a catalyst to exacerbate the destruction of the ozone layer. The alumina can increase the destruction process by nearly 22%[2]. While the process of global atmospheric circulation will keep the ozone layer stable, a rapid increase in launches will lead to the destruction of ozone[2,6]. There are also various other impacts that the emissions can have on the atmosphere. Liquid-propellant fueled rockets that use liquid hydrogen release 97% water[6]. However, due to the plume that comes from the rocket, the water that is present can increase the number of mesospheric clouds, which can result in disrupted communications between satellites[2]. This can have a serious impact as the study on this topic is limited and scientists do not have much information regarding the specific impacts that the mesospheric clouds have with current technology. Radiative forcing is another phenomenon that is exacerbated by rocket emissions[2]. The gases and particles from the emissions will trap the sunlight's heat and create positive radiative forcing which heats the atmosphere. A greater increase in launches can lead to greater positive radiative forcing and climate change. Emissions such as black carbon can impact global warming at a rate 105 times more than carbon dioxide and potentially warm the stratosphere[6].Chemicals such as hydrogen chloride can impact local water ecosystems by significantly altering their pH levels and creating massive fish kills as a result of eutrophication from hydrogen chloride[6]. Unsymmetrical dimethylhydrazine fuel that is used in liquid rocket engines can leave land obsolete for 34 years[6]. Dallas' paper is strong in identifying the various problems that emissions may have on the Earth's atmosphere, and there is a recurring theme of how a significant increase in launches can permanently damage the Earth. It also does a good job of using tables and diagrams that are easy to read and help the reader gain a greater understanding of the language that is used in the paper. However, while his comprehensive literature review is accurate in finding the things that already harm the environment, his work fails to address the newer impacts that are being made by industry. Most of his work is cited by studies that have been completed before the 2000s. His work analyzes many rockets and propellants that are somewhat outdated and are not used in today's launches. For example, his table regarding the most commonly used fuels cites work from the 1990s to 2000s, which is relatively outdated regarding the current state of the industry[6]. While these fuels are often used, it would be unreasonable to think that the information on the impacts of these fuels that were documented in the 1990s-2000s would not have new impacts. With the newer technologies present, the 20-year gap in research on these fuels is a weakness, considering the paper was published merely 3 years ago. On top of that, Dallas' review is structured very poorly. The paper is divided into sections regarding the topics, summarizing various papers that are analyzed regarding the impacts they were searching for. Moreover, most of the body is a summarized version of all the papers he researched and a lack of analysis from his perspective regarding any of the problems. He merely restates the facts from all of the papers that were researched and adds that it indicates danger. With no room for analysis, you can merely see a glimpse of the author's opinion in the introduction and conclusion. Sirieys' research mimics a lot of Dallas' literature review. However, Sirieys can provide more analysis compared to Dallas' review. It is stronger than Dallas' review as Sirieys' research created a comparison between the present effects and the future effects by considering the growth trends of space launches. It also acknowledges various gaps within the research such as the lack of severe impact to date has not sparked the need for greater research on the topic. Various sections in the paper provide various options on what could be done to solve these problems, such as including greater regulation or creating greater incentives for manufacturers to create environmentally friendly rockets. However, some concerns arise throughout this paper as well. While there are various sections provided with analysis from the author, the claims that are made for moving forward seem slightly difficult to implement. For example, in the section about solutions for the rocket emission problem, Sirieys says that immediate action that is taken by creating rules for sustainable manufacturing will help to alleviate the problem in the future[2]. While using an alarmist tone is important for this paper, it is also important to consider the actual success of this happening. For these rules to be established they would have to be accepted by various governments across the world and there would have to be a substantial desire to pass this. Moreover, Sirieys goes on to state that sustainable design changes may or may not have a substantial impact depending on how the initial designs are created[2]. Using this sort of reasoning is relatively unconvincing as it displays a lack of potential success. If the designs made are not certain to be successful, how will they convince others that they are needed to save the environment?

Space Debris

Space debris is another serious problem for space sustainability, but various models have been created to determine the current state of debris and its future. Lewis and Marsh created and analyzed various predictive models to demonstrate the rapidly growing space debris population[7]. While the threat of an exponentially growing space debris population looms on us, some solutions are already being used to monitor and hopefully help mitigate risks. Mehrholz and Leushacke discuss the current state of space debris and describe how the FGAN Tracking and Imaging Radar system is used to detect objects in space[8].

But why is space debris a problem for space sustainability? As satellites orbit around Earth, there are little chunks from destroyed satellites that will be traveling at very high speeds that are also orbiting. If they hit each other, it can permanently damage a satellite and make it obsolete. For example, the French Cerise reconnaissance satellite was an operational spacecraft that had been hit by a piece of debris from an Ariane 5 launcher, resulting in severe damage[8]. However, the collision may fragment the satellite, creating more space debris. As more collisions happen, there will be greater fragmentation and more space debris. Space debris creates clutter around the Earth's orbit, giving various satellites and launch vehicles more hazards to avoid. This makes it harder for satellite longevity and can result in various failed missions.

Space sustainability is a topic that is garnering more conversations than it has before. With rules that are being established by organizations such as the Inter-Agency Space Debris Coordination Committee. However, Lewis and Marsh provide a unique perspective in addressing this concern. Their models take the consideration of deep time, which means they look to analyze impacts hundreds of years into the future. The consideration of deep time is the best part of their research. Deep time actively shows us what problems will occur after a long time and can give us a better scope of what solutions we can use to solve the issue.

Their study focuses on two main values to determine the deep-time effects of space debris, the finite rate of population increase and the intrinsic growth rate (the contribution of an individual to the rate of change in population size)[7]. From the models that Lewis and Marsh created, the change in the intrinsic growth rate from the period 1981-2006 to the period 2006-2021 indicates a 75% increase[7]. This already shows the impact that has been made from the commercialization of the space industry in the 2000s. This increase can be associated with the trend that was seen in Sirieys' research, where there was a 54% increase in commercial launches[2]. Both of these increases show that there is a correlation between the greater number of launches and the increasing growth of space debris. As these launches grow, there will be a greater chance of a collision with space debris resulting in more fragments which creates more space debris.

Using these models that they created, Lewis and Marsh made computer models to simulate how these growth levels would be dangerous in the deep time. Their model simulated the growth of space debris for the next 1000 years[7]. Their models were effective at showing how the current solutions to this space debris would impact the solutions. They state that their models show that there still will be exponential growth of space debris, even with the guidelines that are currently set by the Inter-Agency Space Debris Coordination Committee. This shows how necessary it is to create effective space guidelines that will be sustainable. The main problem with the current guidelines that are set is that they are focused on the present. The rules do not take much consideration of how space debris may change in the future. Instead, it focuses on the current state of space debris and that creates a very poor solution.Lewis and Marsh's DAMAGE model proves that there is limited efficacy when using these rules[7].

However, while the research that they did does have very strong findings, there are some weaknesses in how they created the models for their research. For example, the models that they used considered all pieces of space debris to be equal in population, which means that size and shape were both disregarded. While this would be extremely difficult to do using today's technology, it does show that there is a weakness in the results that they found. On top of that, while addressing the deep time is important to consider, creating rules based on that is extremely difficult. Throughout the paper, Lewis and Marsh advocate for the creation of including deep time whilst creating guidelines[7]. However, this is extremely difficult as rule creation using deep time can end up becoming too broad, and hard to create an achievable goal.

While there is difficulty in finding a solution to the issue of space debris, there are technologies available that can be used to help solve it. To identify space objects, the European Space Agency (ESA) uses the FGAN Tracking and Imaging Radar system. The FGAN Tracking and Imaging Radar system is pointed to a predetermined position in space[8]. After an object is detected, it is tracked and observational vectors are collected[8]. To characterize the smaller space-debris environment, the ESA uses the FGAN Tracking and Imaging Radar system for beam-park experiments[8]. In this mode, the radar beam is maintained in a fixed direction (concerning the Earth) and all objects that pass through the beam are registered[8]. For one day, the rotation scans the beam through 360 degrees in inertial space[8]. From the backscattering of the radar signal, the FGAN Tracking and Imaging Radar system will determine the size of the object and some of its orbital parameters[8]. With this information, the FGAN Tracking and Imaging Radar system can be used to validate space debris models[8].

However, while these technologies can be found in more developed space agencies, it would be hard to characterize the entirety of the space debris environment without various programs having technology like this. However, access to greater technology falls under the rat race to succeed again. The most successful programs can launch numerous times and they work on launching as frequently as they can to ensure that they have the best possible position in this growing field of research. The only way that there can be an accurate measurement of the space debris field is that the information that is already known must be shared and space agencies across the world have to share the research that is used to characterize the environment[7]. This would create an opportune playing field and help to advance the space industry even faster than it has before.

The ever-growing space industry will only continue to increase as more space launches are conducted every year. Unfortunately, the research currently available about space sustainability is severely lacking.Every piece of literature that has been covered in this review states the necessity of greater research[2,6–8].Throughout all of the literature that has been covered, there have been many gaps of knowledge. For example, issues such as space objects returning into the atmosphere have been neglected[2,6]. The emissions that are caused by re-entry are also not considered and as Sirieys states, unknown[2]. The ways that emissions could impact the regions above the stratosphere are unknown, and the predictive models that were used by Lewis and Marsh do not provide much accuracy for what is to come[2,6,7]. However, the literature that has been covered does identify the problems that are known and offer solutions to what has to happen next. Further research is a must to more clearly categorize the problems that rocket emissions and space debris have on Earth's environment.

Methods

To investigate the impacts that space debris and rocket fuels have on space sustainability, there was an analysis of available research on rocket launches. Data was collected from sources such as academic articles, government reports, and databases to discover the impacts that they have on space sustainability.

Data was gathered into two separate spreadsheets, one about space debris and one about rocket fuels. Then, data was compiled and organized into various categories such as launches per year, average launch mass, specific impulse, types of propellant, and other categories.

To observe the impact space debris had on the environment, a database that provided a list of almost all satellite launches that have occurred across the world was analyzed. The analysis of this database focused on finding growth trends in the space industry and what implications that can have for space sustainability. The data was organized into various categories that were relevant to the search for the growth of industry and space debris population. Some data points were omitted on nearly all the sets since some satellite launch information was incomplete.

To observe the impact rocket emissions had on the environment, an analysis was conducted of data gathered by NASA about various propulsion systems. The analysis focused on quantities that can identify signs of how rocket emissions impact the environment and how these systems damage the environment due to their design. The data was organized into various categories to help determine certain effects that these rockets can provide. Some data points were omitted from nearly all the sets because some information on the launch systems was incomplete.

Results and Discussion

To present the findings, several graphs and charts were created to illustrate the impact that space debris and rocket fuels will have on space sustainability. These graphics help to demonstrate the impact that rocket launches have on space sustainability and provide some insights into possible solutions to help solve this crisis.

The methods that were used primarily focused on collecting and analyzing data from various sources and presenting these findings using graphics. These graphics help to provide insights into what is required for the future of the space industry and how the environment has been impacted throughout the history of space launches.

Figure 1 represents the total number of recorded satellite launches from 1988 to 2022. Note that the number from 2022 was calculated using a linear estimate based on information from the database that there were 699 launches in the four months that are recorded for 2022.[9]. The growth trend that can be seen in Figure 1 can be described as exponential and could pose catastrophic consequences for the space industry. This is consistent with the trends that were described in Sirieys' research which showed a massive upward tick in growth beginning from the 2000s. However, the 375% increase in satellites from the year 2019 to 2020 and a 187% increase from 2020 to 2022 is frightening. With such a large jump from 2019 to 2020, even more growth can threaten the atmosphere and greatly increase the population of space debris[2,6,7]. Various effects such as ozone depletion and mesospheric cloud formation could plague the Earth's atmosphere.

However, the linear estimate is not an accurate number regarding the growth trend that is displayed. The number of satellites

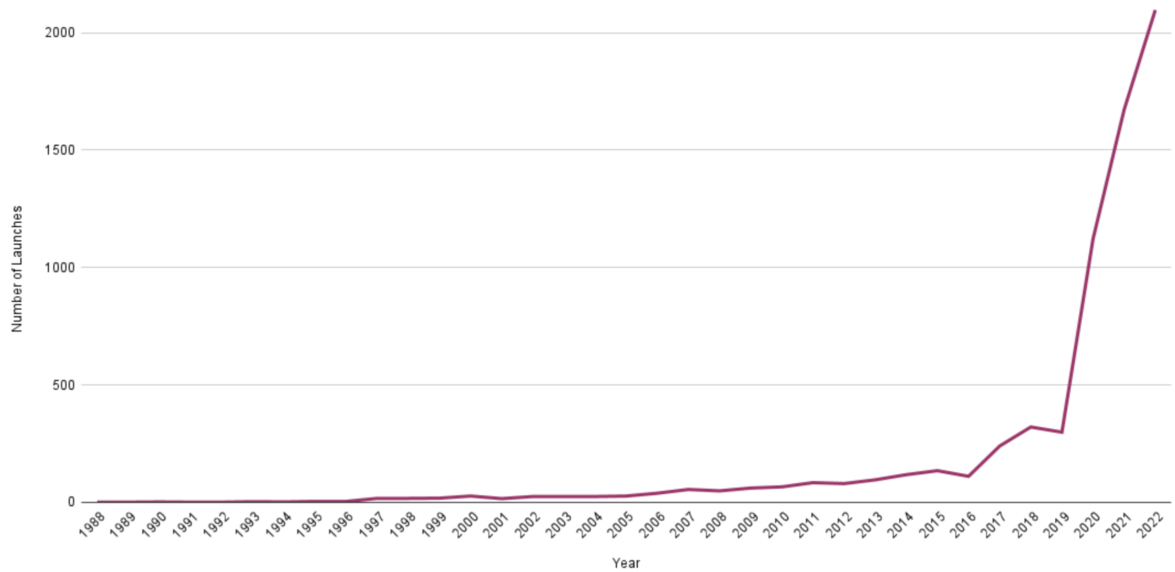

Fig. 1

was calculated using simple algebra. However, the calculation did not take into account factors such as the upcoming projects of space organizations, adequate days for launching, quality of launch sites, upcoming research goals, and many others that could significantly affect the rate at which space agencies or companies launch. The 2022 estimate only provides partial accuracy as it was able to account for the launches for the first four months of the year. More recent data would have to be analyzed to measure how accurate the estimate was.

Figure 2 and Figure 3 represent the distribution of major industries that use satellites in the US. They were divided into 4 industries, Civil, Commercial, Government, and Military. The orbit that these satellites are in is also listed in this table. Figure 2 and Figure 3 describe the distribution of satellites that are in orbit for the United States. The proportions of satellites were divided into four categories: Civil, Commercial, Government, and Military. Note that most satellites come from commercial use in America.

Sirieys notes how more of the launches that are happening as of 2002 have been from commercial industries[2]. With increased commercial launches, it will be harder to maintain more regulations as many of these private companies will want to launch as much as they can to generate more profit. It brings us back to that rat race idea, where companies are struggling to get the latest edge to become a superpower in the field. One important thing to look at is how lots of the satellites that are being launched into space are in Low Earth Orbit (LEO).LEO can create greater challenges for space launches. For example, the relatively low height of LEO creates more obstacles for things that are being launched past LEO. On top of that, 90.8% of all of these satellites have been launched into LEO. This shows that the LEO has the highest chance of having the most clutter[7,8]. The greater the number of satellites, the greater the chances of creating more debris, which could impact both satellite functionality and other spacecraft going past LEO orbit. It is also important to look at the distribution. Commercial industries have most of their satellites in LEO, indicating the rush to move into the space industry. However, the data does have some inconsistencies.

Although the commercial industry has the highest percentage of satellites having a LEO, all of the other industries (Civil, Government, and Military) do have a majority of their satellites in LEO. However, the high percentage of LEO satellites indicates that there is a greater probability of clutter[7,8]. The data is also inconsistent in the fact that it is hard to determine the idea behind each of the goals that are present in these graphs. The purpose of a satellite is different between each of the industries, and the figures do not provide information about the ideas that the satellite launches were a part of. This makes it hard to identify whether these companies were working to establish themselves within the space industry or for other purposes (such as surveillance or gathering data on Earth) that could transcend the space industry.

Figure 4 compares the number of launches that occurred in the US and the rest of the world from the years 1998 to 2021. Figure 5 zooms into the previous figure with a range for 2001-

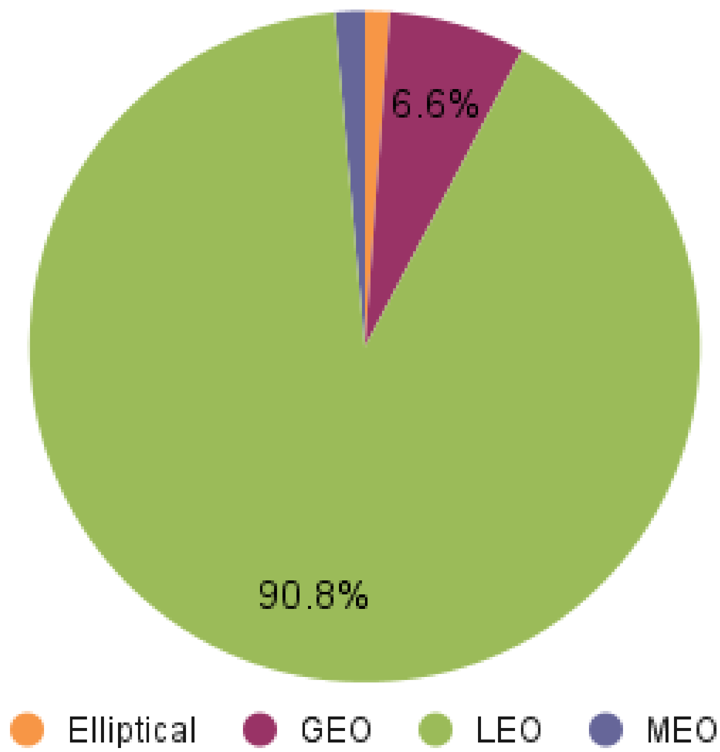

Fig. 2 [9]

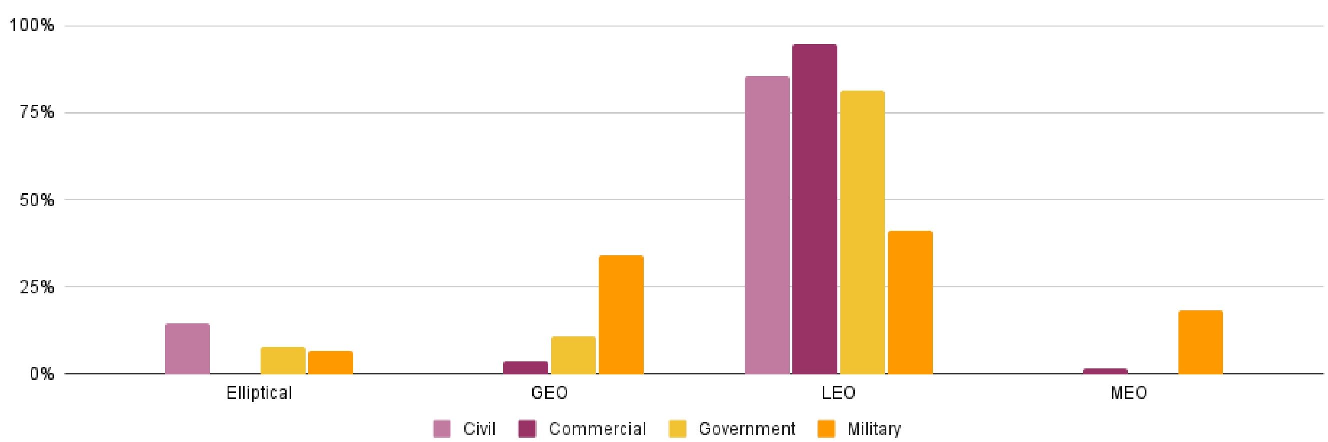

Fig. 3 [9]

2021. Figure 4 and Figure 5 compare the number of launches that were conducted in the USA compared to the rest of the world. Figure 6 compares the launches by major space countries (organizations) such as the USA, Russia, China, India, and the ESA. The data that has been gathered for this graph ranges from 2009-2022. Note there are gaps in the data in the years 2021 and 2022. For 16 separate years, the USA was able to overperform the rest of the world. This shows how influential the USA has been in the space industry. This influence, however, dictates the way that the space industry will move forward. Many consider

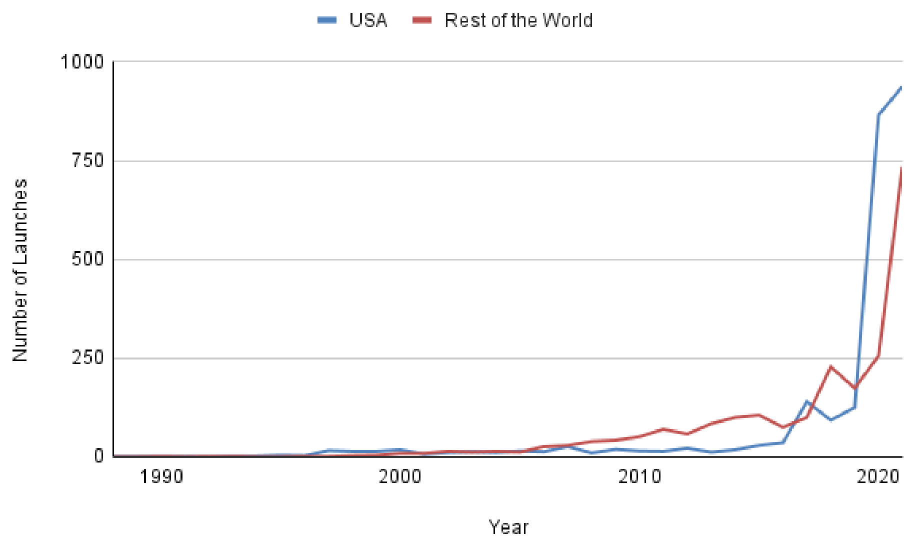

Fig. 4 [9]

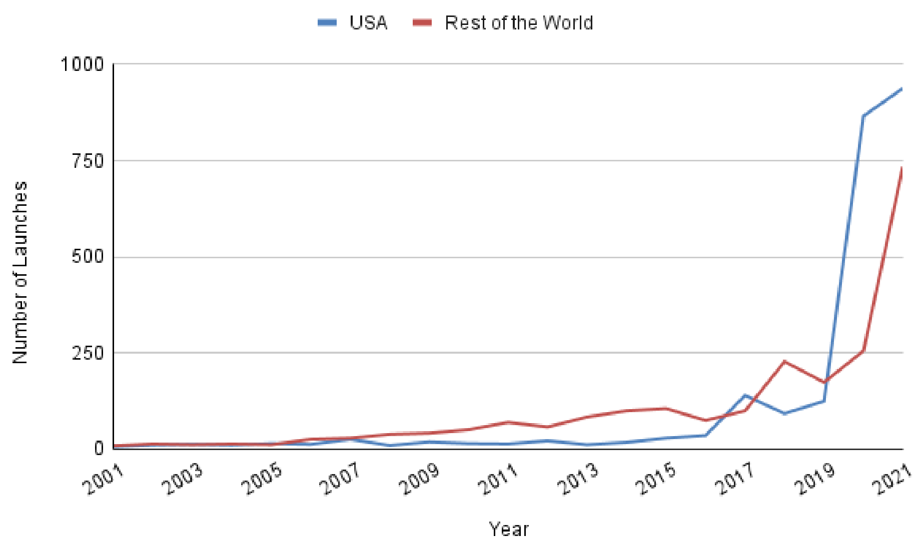

Fig. 5 [9]

that NASA is a profound figure in the space industry and their research tends to be at the forefront. Without a transition to researching more about the impacts that space debris and rocket emissions can have on space sustainability, it might be harder to effectively create a solution that will be implemented across the world. With the USA being a critical figure, they must be at the forefront of regulation for the space industry. Lewis and Marsh, as well as Sirieys, request additional regulation on rocket launches due to the environmental impact as well as the increasing space debris population that is growing from the rapidly expanding space industry[2,7] While creating incentives might be a solution for solving this problem, that depends on a country-to-country basis and could be detrimental for the growth of some space industries. Without an established industry, it can be hard to implement substantial research on these topics. However, it is also important to consider the growth of some other countries

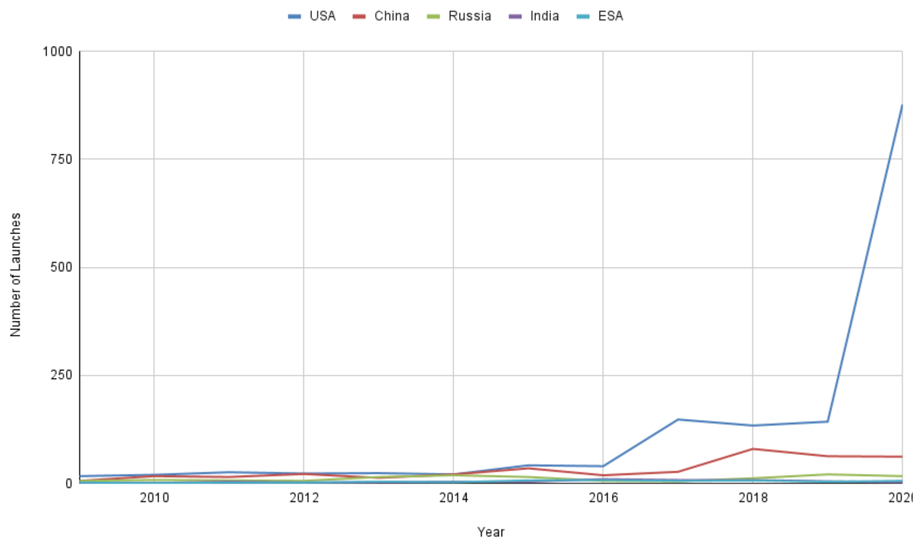

Fig. 6 [9]

that may have ulterior motives for space. For example, countries such as China and Russia which have extremely central governments, may end up hiding research that has been completed regarding space and that could diminish the capability that they possess. While the USA is a prominent figure, the rest of the world must also work to establish solutions regarding these issues. The results also come up short of displaying what kind of industries are at the forefront of these launches. The graph does not show the types of industry that are launching the most rockets for each company, and that can make it difficult to understand the capabilities of each country's space industry.

Figure 7 describes the trend of the average launch mass of all satellites from 1988-2022. Figure 8 compares the average launch mass of different satellite classes from 2006 – to 2022. Figure 9 compares the all-time average and standard deviation of the classes per year. Note there are gaps in the data from 1998-2005. Figure 7, Figure 8, and Figure 9 discuss the launch mass of satellite launches. It is important to note that there is a considerable decrease in the launch mass for these satellite launches. This can be a good and bad thing at the same time. These smaller instruments offer a clue to one way that companies can conserve. It shows that the industry can engineer new solutions and could instead focus more on sustainability. As Sirieys et al. say, incentivizing the creation of space-sustainable rockets will allow for problems such as the danger of rocket emissions to slowly diminish[2]. However, with the smaller launch masses, there also is a concern with space debris. While the instruments have begun getting smaller there is also a considerable growth in the number of rockets that are sent into space. Companies such as SpaceX led the number of satellites that were launched into space by the USA. Even greater numbers of satellites create a greater risk for collisions and could create even more space debris. The lower satellite launch creates a greater risk of creating minuscule pieces of debris. Smaller pieces of space debris are dangerous because they can easily travel at high speeds which creates a higher risk for satellites to fragment and become obsolete. One important thing to notice is that the standard deviations of these satellites are extremely large. This means the data is extremely varied and that the mass of each satellite will be extremely different. The variance creates poor trends in the data and the trends shown in the graphs may not be very true. There are also some years of data where there are merely 4 or 5 satellite launches and that doesn't provide a very good number for average satellite mass in one year.

Figure 10 shows the average life expectancy of satellites from the years 1990-2022. Note that there is a gap in the year 1992 as no data was recorded for life expectancies that year. Figure 11 compares the average life expectancy of satellites that are in LEO, Medium Earth Orbit (MEO), and GEO orbits. Note there are gaps in the data in the years 1990-1996, 1998, and 2022. Figure 11 compares the average expected lifetime for all satellites over the years 1990 - 2022. It is especially important to look at the LEO satellite lifetimes. Due to the majority of current satellites present in LEO orbit, the lower lifetimes create a greater opportunity for debris to arise in the form of zombie satellites or collisions. It is crucial to look at the ever-increasing decline of the lifetime of these satellites. While the lifetime of these satellites was initially increasing, there has been quite an abrupt drop near the 2000s, which is when many commercial satellites have been going into space. A lower expected lifetime

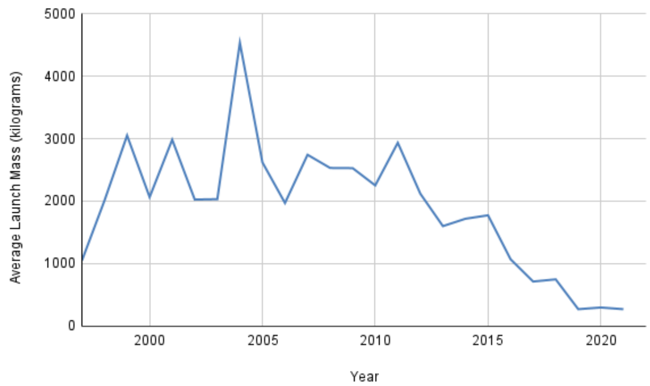

Fig. 7 [9]

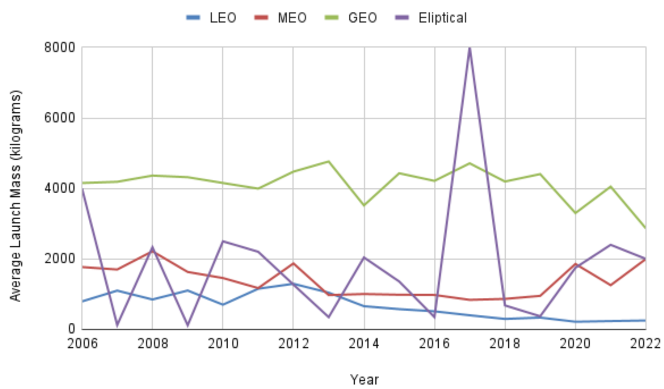

Fig. 8 [9]

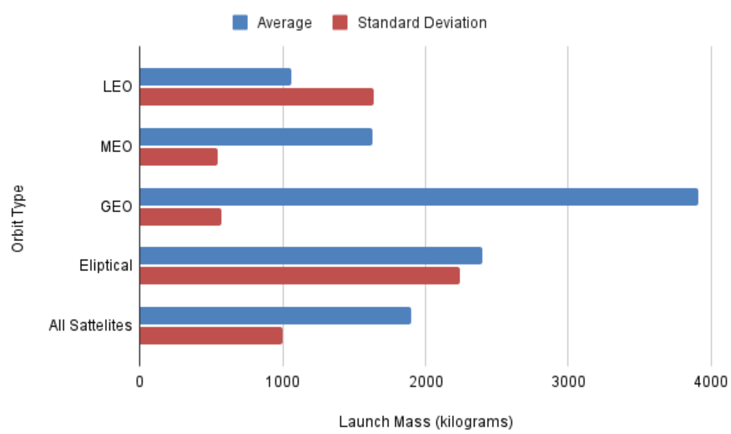

Fig. 9 [9]

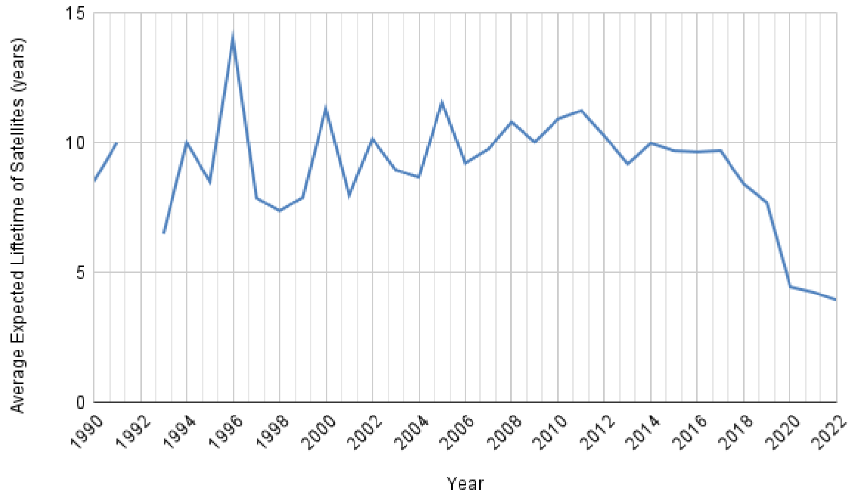

Fig. 10 [9]

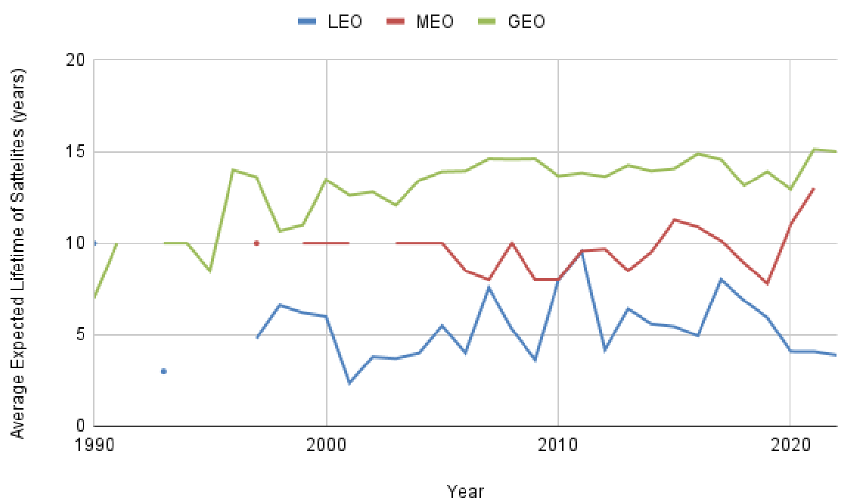

Fig. 11 [9]

paired with the rapid growth of rocket launches creates a greater possibility of zombie satellites. Zombie satellites are satellites that are orbiting Earth but possess no functionality whatsoever. These satellites are dangerous because they pose a large threat of colliding with another satellite or space instrument and creating a lot of minuscule debris that can be dangerous for launches[8]. Add the fact that the previous graphs indicate a lowering average satellite mass, this can be extremely dangerous. The smaller satellites with lower life expectancies will become hazards to the other satellites that are present in orbit and will create a greater chance for more satellites to be destroyed and create even more debris. While Mehrholz and Leushacke do discuss the possibility of detecting more space debris with radar imaging, microscopic pieces of debris will still exist which could threaten many rocket launches[8]. However, the various gaps in the data do not help to support the trend in the average lifetime of these satellites. On top of that, there are various years where only a few satellites were launched which does not give an accurate measure of the average lifetime of these satellites.

Table 1 compares the chemical formulas and emissions of some of the most used propellants that are used for rocket launches. For the emissions, the emission product chemical

Propellant Name	Chemical Formula	Main Emission Products	Main Emission Product Chemical Formula.
Ammonium Perchlorate Composite	$Al/NH_4ClO_4 \pm HTPB$	Hydrochloric Acid, Water, Carbon Dioxide, Nitrogen Oxides, Aluminum Oxide, Soot	$HCl, H_2O, CO_2, NO_x, Al_2O_3,$
Liquid Hydrogen Fuel and Liquid Oxygen Oxidizer	LO_x/LH_2	Water, Hydrogen, Hydroxide, Nitrogen Oxides	H_2O, H_2, OH, NO_x
Unsymmetrical dimethylhydrazine	$N_2O_4/UDMH \pm N_2H_4$	Water, Nitrogen, Carbon Dioxide, Nitrogen Oxides, Soot	H_2O, N_2, CO_2, NO_x
RP-1 (kerosene)	$LO_x/RP-1$	Carbon Dioxide, Water, Carbon Oxides, Hydroxide, Nitrogen Oxides, Soot	$CO_2, H_2O, CO_x, OH, NO_x$

Table 1 [2,10]

formula list is respective to the emission product list. Note that soot's chemical formula is not listed due to its varied forms. One thing to note is the presence of chlorine in emissions. Chlorine emissions were one thing that both Sirieys and Dallas states were extremely detrimental to the environment, as they depleted ozone[2,6]. Chlorine emissions were present in one of the fuels, Ammonium Perchlorate, which is a solid fuel. The other fuels that were present contained other oxides that are proven to lead to climate change, but all of the fuels contain water. The water that is present could lead to mesospheric cloud formation, which has unknown effects on the environment. It is also important to note that the frequency of launches, combined with these emissions could create a significant impact. Dallas and Sirieys state that an increase in launches would exacerbate the impacts that these emissions already have on the atmosphere or the environment. However, these fuels are merely the most commonly used in rockets. The table doesn't provide any data regarding other types of fuels that may be used. It also doesn't consider the fact that there may be other sustainable fuels that are being developed that could be used in the future. However, these fuels do provide substantial information on what kinds of gases are going into the Earth's atmosphere and help us understand what those gases may do to the atmosphere.

Table 2 and Figure 12 compare various propellant technologies. The table compares the various ranges of thrust and specific impulse. The graph compares the high specific impulse and the low specific impulse. Table 2 and Figure 12 compare the different launch technologies that are used for these satellites. It is interesting to note that the rocket technologies that are harmful to the environment are much more effective compared to other launching methods. The propellants that have the lowest specific impulse ranges are the ones that will be the most effective as they will be able to apply thrust the quickest. So, while various sustainable options can be used in rockets, none of them can provide enough thrust in a short period compared to less sustainable options. However, if engineers were able to create a solution that would lessen the impact of emissions on the atmosphere, that would help us continue to use these effective fuels. However, the data that is shown doesn't give enough information on how the technologies of each of the systems work. By merely providing the thrust and the specific impulse it is hard to determine how these systems function and determine whether these technologies could be improved to use in the future.

Conclusion

Space sustainability is an important issue that requires immediate attention. The growth of the space industry and continued use of space for commercial and scientific purposes must be done responsibly and sustainably. Space is a valuable resource and by being able to successfully harness it the space industry may be able to learn about solutions to problems that have never been done before. Implementing solutions such as identifying newer alternatives to detect space debris, incentivizing companies to make more sustainable rockets, and creating stricter guidelines for the space industry can make this invaluable resource last longer. The space industry must work for space sustainability, because, without it, they may not be able to unlock a much brighter future for humanity.

This research focuses on two key issues: rocket emissions and space debris. Data has been gathered regarding the trends of satellite launches over the history of the world's space industry and analyzed to observe how the impacts made by these rockets could be exacerbated. There are various problems that emissions could have on various parts of the earth, such as the launch sites, ozone layer, stratosphere, and mesosphere. On top of that, the threat that space debris provides could limit further missions due to the damage that it can inflict on various instruments

Types of Propellant Technologies	Thrust Range Low (N)	Thrust Range High (N)	Specific Impulse Range Low (sec)	Specific Impulse Range High (sec)
Hydrazine Monopropellant	0.25	25	200	285
Alternative Monopropellants and Bipropellants	0.01	120	160	310
Hybrids	1	230	215	300
Cold / Warm Gas	0.00001	3	30	110
Solid Motors	0.3	260	180	280
Electrothermal	0.0005	0.1	50	185
Electrosprays	0.00001	0.001	225	5000
Gridded Ion	0.0001	0.02	1000	3500
Hall-Effect	0.001	0.06	800	1950
Pulsed Plasma and Vacuum and Arc Thrusters	0.000001	0.0006	500	2400
Ambipolar	0.00025	0.1	400	1400

Table 2 [10]

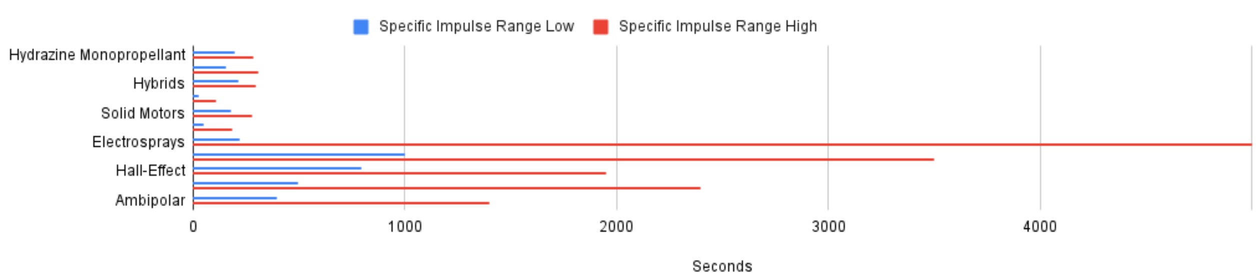

Fig. 12 [10]

in orbit. At the rate at which the space industry is growing, the large increase in space launches exacerbates the problems that are already present with rocket emissions and space debris. Greater research is a must to ensure that these problems don't get destructive.

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