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Impact of Spaceflight on Earth's Atmosphere: Climate, Ozone, and the Upper Atmosphere

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Impact of Spaceflight on Earth's Atmosphere: Climate, Ozone, and the Upper Atmosphere

[Current Understanding, Knowledge Gaps, and a Proposal for a Multi-Agency Multi-Year Scientific Study to Fill-in the Gaps and Develop an Impact Assessment Capability]

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I. Preface

New space technologies and commercial opportunities in orbit have given rise to an exponentially growing and fast changing global space industry. Rocket launches and reentering satellites and upper stages emit gases and aerosols into every layer of the atmosphere from Earth's surface to low earth orbit. These emissions potentially affect climate, ozone levels, mesospheric cloudiness, ground-based astronomy, and thermosphere/ionosphere composition. The space industry growth rate is impressive: launch and reentry mass fluxes have recently been doubling about every three years (Lawrence et al., 2022). Space activities will continue to increase, according to industry projections, by at least an order of magnitude by 2040 (Ambrosio and Linares, 2024).

The space industry is being transformed by large Low Earth Orbit (LEO) satellite constellations so that by 2040 planned systems will require more than 10,000 satellites to be launched and disposed of into the atmosphere each year. Heavy lift rockets powered by liquid Natural Gas (LNG) fueled engines are expected to dominate launch activity by 2040 (Dominguez et al., 2024). The scope and character of space industry emissions into the atmosphere is radically growing and changing (Shutler et al., 2022).

Estimates of launch and reentry aerosol emissions indicate that the many planned large LEO constellations will require an increase in launch tonnage from the current 3,500 tyr^{-1} to over 30,000 tyr^{-1} by 2040 (Shutler et al., 2022). Rocket combustion emissions will increase in step with payloads. Reentry emissions from vaporizing space debris and spent rocket stages will increase from the current 1,000 tons per year to over 30,000 tons per year (Shulz and Glassmeier 2021). By 2040, the total global flux of launch and reentry particulate (Black Carbon and metal oxides) emissions into the stratosphere will be comparable to the natural meteoritic background flux. These estimates do not include the uncertain but possibly significant launch requirements of new space systems in orbits such as MEO (Medium Earth Orbits) and GEO (Geostationary Equatorial Orbits) or of an aggressive program of Moon or Mars exploration. effort.

This uptick in launch and reentry emissions is occurring in the face of widespread knowledge gaps regarding the composition and chemistry of spaceflight emissions. Very little is known about the emissions and impacts from large LNG rockets. The recent discovery that metals from reentering space debris are already present in 10% of the particles that make up the natural stratospheric sulfate layer emphasizes the urgent need to understand how the coming order of magnitude increase in reentries could affect the atmosphere (Murphy et al., 2023). The overall lack of the scientific and engineering models, tools, and data required to assess the impacts of future spaceflight emissions is clear.

The Knowledge Gaps:

Responding to these growing concerns, in 2021, Dr. Surendra P. Sharma, NASA Ames Research Center, organized and lead a multi-agency working group (Dr. Martin Ross, The Aerospace Corporation; Dr. Karen Rosenlof , NOAA/CSL(National Oceanic Atmospheric Administration/Chemical Science Laboratory); Prof. Chris Maloney, NOAA CSL Chemistry & Climate Processes Group, University of Colorado; Kostas Tsigaridis, University of Columbia; and Dr. Gavin Schmidt, GISS/NASA (Goddard Institute Space Studies/National Aeronautics Space Administration), supported by NASA's internal funds (Earth Science Division) to analyze the validity and credibility of models that predict the global impacts of launch and reentry emissions and the data that is available to validate the models. The group identified key gaps in fundamental scientific understanding of the phenomena including modeling techniques and data collection capabilities that will need to be overcome before the impacts of the space industry can be credibly assessed to a level commensurate with the anticipated growth. The fundamental gaps in scientific understanding put the space industry, and the commercial and government organizations that depend on it, at risk from unanticipated environmental impacts. Resolving the knowledge gaps before the anticipated growth and change occur is a low-cost risk reduction program. The group's analysis is supported by other studies about spaceflight emissions including the American Astronomical Society (AAS) (Venkatesan, 2024) and the Government Accounting Office (GAO, 2022). ESA (European Space Agency) is pursuing an independent "Clean Space" project along similar lines (ESA,2024).

The Proposed Study:

In order to eliminate potential risk from the lack of scientific understanding and resolve the current inability to assess how a rapidly growing space industry will affect Earth's atmosphere, a well-defined research effort is recommended. As demonstrated in the white paper "Impacts of Spaceflight on the Global Atmosphere: Current Understanding, Knowledge Gaps, NASA's Role, and Roadmap (Ross et al., 2022 and 2024) [see Appendix II], we must improve our ability to model and observe rocket engine combustion, far field rocket plume evolution, impacts on the upper atmosphere, global launch impacts, reentry gas and aerosol production, far field reentry plume evolution, and global reentry impacts. The highly successful Atmospheric Chemistry of Combustion Emissions Near the Tropopause (ACCENT) program[2] (Ross et al., 1999; NASA, 2024) serves as a model for the proposed effort. ACCENT was a multiagency research program that included observation and modeling of rocket plumes and played a critical role to remove the threat of regulatory action against the Space Shuttle's solid rocket motors[3]. A similar effort today would be a combination of remote, in situ, and laboratory measurements that feed into model development and assessment of future launch and reentry emissions.

A proposed sequence of investigations and studies would include (in order of prioritization):

1. Remote sensing of satellite and upper stage reentry plumes during vaporization phase and afterward as the plume cools and is transported and diffused by stratospheric winds.
2. Determine which reentry phenomena and processes (like ionization, disintegration, vaporization, aerosol formation, metal alloy kinetics) need better data and models. This can be done by using the existing modeling codes to simulate the acquired data from item # 1. Essential reaction rate data on some of these processes must be measured in a controlled laboratory environment.
3. In situ measurement of exhaust plumes from LNG fueled rockets after launch. We plan to collaborate with NOAA flying the SABRE (Stratospheric Aerosol processes, Budget and Radiative Effects) payload on NASA WB-57F aircraft (NOAA, 2024)[4]. Participate in remote sensing of far field exhaust disturbances to the upper atmosphere from far field plume observations. Cooperate with AAS (American Astronautical Society) and NSF "Dark and Quiet Skies" initiative (Venkatesan, 2024).
4. Incorporate (a) reentry plume evolution and aerosol production data, (b) launch plume evolution data, and (c) launch ionospheric modification data into global climate models (e.g., ModelE (GISS, 2024), WACCM (Whole Atmosphere Community Climate Model) (National Center for Atmospheric Research, 2024), and TIE-GCM (Thermosphere-Ionosphere-Electrodynamics

[2] https://impact.earthdata.nasa.gov/casei/campaign/ACCENT/
[3] Ko et al. (1995), Better Protection for the Ozone Layer, https://www.nature.com/articles/367505a0
[4] https://csl.noaa.gov/projects/sabre/science/schedule.html

General Circulation Model) (University Corporation for Atmospheric Research, 2024) and validate updated models with the remote and in situ observations of reentry and launch plumes (items 1.- 3. above).

5. Develop an assessment methodology based on these modified and validated global climate models with realistic emission specifications based on the data validated plume models.

Following this carefully planned process, the technical community will be able to develop credible assessment data and simulations that can be used to accurately assess the impacts of launch and reentry emissions on the global atmosphere. The scientific publications from this effort will be used to support reviews and assessment such as the World Meteorological Organization and Intergovernmental Policy Climate Change ozone and climate technical reports.

We have provided an overview [details are available in Appendix] of a carefully planned multi-year and multi-agency effort based on a highly successful antecedent. Every member of the group has extensive experience in conducting similar research. Two agencies (NASA and NOAA) have existing resources (airborne platforms, sensors, and models), which can readily be deployed and applied to this proposed effort.

Relationship to Agency's Space Sustainability Initiative:

NASA's recently announced Space Sustainability Strategy (NASA, 2024b) is committed to understanding how the space industry can be developed and grown in a sustainable manner and to the development of widely adopted best practices, analytic studies, models, technologies, and operations for the benefit of all. The initial focus is Earth orbit and the management and mitigation of space debris. This is usually assumed to mean safe launch of rockets and disposal of space debris into Earth's atmosphere.

NASA's Space Sustainability Strategy says, "understanding the associated risks and benefits of new and existing capabilities is crucial for space sustainability," and the proposed research effort directly supports and is in accord with NASA's efforts at Space Sustainability. As we have demonstrated, launching payloads into orbit and the subsequent disposal of rocket engine combustion, upper stages, and retired satellites into Earth's atmosphere (some disposal is done to graveyard orbits) affect Earth's atmosphere in ways that could be detrimental to the atmosphere and other human pursuits (e.g., astronomy.) The activities involved in Space Sustainability are operational in nature, and the prerequisite is that we understand what is being emitted by space vehicles during launch and reentry, what is the fate of these emissions, and how these emissions affect the atmosphere.

The American Astronomical Society has determined that launch activities cause changes in upper atmosphere cloudiness and visible light emissions, which could impact the performance of government investments in ground-based astronomy. Finally, the WMO (World Meteorological Organization) Quadrennial Assessment of Ozone Depletion 2022[5] notes that the significant unknowns regarding spaceflight activities prevent a reliable assessment of their contribution to global ozone layer loss and recovery. The 2022 Assessment (Chapter 6) concludes about spaceflight emissions "…further research is warranted."

[5] https://csl.noaa.gov/assessments/ozone/2022/

It Must be a Multi-Agency Project in Collaboration with the Private Sector and International Partners:

In the interests of efficiency and low cost the proposed "Impact of Spaceflight on Earth's Climate, Ozone, and Upper Atmosphere" study must be a multi-agency venture with shared cost and responsibilities with the US space industry and international partners, very similar to the ACCENT project launched during 1990s[6]. The European Space Agency, a US partner in the space industry that has already advanced important research in this area, could be called on as a partner. Following this very strategy, we approached three of our major partners (NOAA, NSF and NASA) for our upcoming spring-2025 workshop "The Impacts of a Growing Space Industry on Earth's Atmosphere: Research Challenges and Opportunities: A Workshop" and confirmed a commitment of $100,000 from each of these partners. The effort would include cooperation with FAA (Federal Aviation Administration) and FCC (Federal Communications Commission) as the agencies responsible for space regulation.

The Urgency of the Situation:

As the first definitive measurements of pollution in the stratosphere from spacecraft reentry were published in 2023 (during NASA WB-57F aircraft carried by NOAA),[7] it has become clear that the possibility that space debris reentry could damage the atmosphere which has become of strong interest in the technical, social media, and national news[8]; respectable organizations like the Public Interest Group[9] and professional societies are voicing their concerns.

Let us recap the scenario of satellite growth as proposed by the space industry. As of June 2024, there are 8,100 objects in low Earth orbit[10], of which 6,000 are Starlink satellites launched in the last few years. SpaceX is the frontrunner in this enterprise, with permission to launch another 12,000 Starlink satellites and as many as 42,000 planned. Amazon and other companies around the globe are also planning constellations ranging from 3,000 to 13,000 satellites. These, when launched, eventually will contribute to the growth of reentry vehicles (burning satellites reentering the atmosphere) in similar numbers (tens of thousands). The demise of a typical 250-kg satellite can generate around 30 kg of aluminum oxide nanoparticles, which may endure for decades in the atmosphere.[11] Aluminum oxides spark chemical reactions that destroy stratospheric ozone, which protects Earth from harmful UV radiation.[11]

With every year's delay in starting a research effort, another 3,000 satellites are launched into orbit.[12] Their carrier rockets and vaporizing de-activated satellites as they fall towards Earth are impacting the atmosphere. Even if we start the study now, by the time we have a credible assessment tool, there would

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[6] EOS (Science News by American Geophysical Union, AGU), Transactions American Geophysical union, Vol. 80, Issue 38; pages 437-442; Sept 1999; Martin N. Ross et al; Study Blazing New Trails into Effects of Aviation and Rocket Exhaust in the Atmosphere.
[7] https://repository.library.noaa.gov/view/noaa/58476
[8] New York Times, Jan 2024, https://www.nytimes.com/2024/01/09/science/rocket-pollution-spacex-satellites.html
[9] https://spacenews.com/connecting-the-dots-fcc-space-sustainability-authority-question-need-grows/
[10] https://phys.org/news/2024-06-satellite-megaconstellations-jeopardize-recovery-ozone.html
[11] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2024GL109280
[12] https://www.spacefoundation.org/2024/01/23/the-space-report-2023-q4/

be as many as 30,000 more satellites[15] in orbit with similar increase in rate of reentry vehicles (satellites) by the time a comprehensive understanding of their effects could be written. Every year the country's civilian, scientific, and military communities become more dependent on the large LEO constellations. Because we have little understanding of their environmental impacts every year brings us closer to a potential environmental surprise where (speculatively) global ozone loss or cumulative ionospheric effects are found to be too large to ignore any longer.

The research must be done before we become dependent upon these constellations, where many hundreds of launches and thousands of reentries take place each year, which potentially may harm the environment of the planet we live on or the planets we will visit in the future.

Economics of Space Flights:

The global space economy grew 7.4% to $0.57 trillion in 2023 and is expected to reach $1.8 trillion by 2035[13]. In 2023, U.S. government space budget was $74 billion, the non-U.S. government space budget was $51.2 billion, the commercial space budget was $321 billion, and the commercial space services budget was $123 billion.[14] SpaceX alone was valued at $180 billion in 2023.[15]

In 2023, 2,877 satellites were deployed into space, which was a 14.6% increase from 2022[16]. The cost each satellite launch varies between $50 million to $400 million[17], which suggests an expenditure of at least $144 billion on building and deployments in 2023. As mentioned in the last paragraph, the space industry plans to increase the total number of satellites in orbit to about 30,000, meaning the deployment rate would have to ramp up to accomplish that. However, for the sake a rough estimate, if we use only a 14.6% rate of annual increase, the deployment expenditure over five years would be $720 billion.

There were about 400 non-satellite related orbital rocket launches in 2023. If we use the 2023 cost of a Falcon 9 cost for all these rocket launches ($67 million)[18] , the total cost of non-satellite related orbital rocket launches computes to $26.8 billion. Over a period of five years, the expenditure would be at least $134 billion.

Summarizing, the cost of satellite building & deployment and other rocket launches over five years would be at least $854 billion.

The overall cost of the proposed study (4-5 years at $7-10 million/year); would be about $0.05 billion. This cost as planned should be shared by prominent spaceflight stakeholder federal agencies and U.S. industries.

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[13]https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/space-the-1-point-8-trillion-dollar-opportunity-for-global-economic-growth#/
[14] https://www.spacefoundation.org/2024/07/18/the-space-report-2024-q2/
[15]https://www.forbes.com/sites/siladityaray/2023/12/13/spacex-reportedly-valued-at-180-billion-in-planned-secondary-market-share-sale/
[16] https://www.slingshot.space/news/state-of-satellite-deployments-and-orbital-operations-2023
[17] https://globalcomsatphone.com/costs/?srsltid=AfmBOopS7uXrYJLiwbLRaTisWbW8bo9t-PJs3b7zj-wY3P37-_tFHX4W
[18] https://spaceimpulse.com/2023/08/16/how-much-does-it-cost-to-launch-a-rocket/

The cost of the study when compared with $854 billion spent over 5 years by spaceflight stakeholders would be only 0.006%.

Now, we compare this to the cost of activities relevant to this study incurred by NASA alone[19]. In 2023 the Agency used about 15-20 Falcon 9 flights (estimates vary) at a cost of approximately $1.2 billion (about $6.0 billion over 5 years), NASA Artemis program's contract to the supplier of the HLS (Human Landing System) to land US astronauts on the moon cost is ~ $4.0 billion (HLS system is slated to use very heavy-lift LNG (Liquified Natural Gas) and SRM (Solid Rocket Motor) rockets). A rough estimate of funds spent on related activities (Rocket launches and satellite deployment) would be at least about $ 30 billion (considering all activities throughout the agency)[20] over five years. The cost our study to NASA, if shared by, for example, 2 other partners (agencies and or industrial partner), would be about 0.05%.

Our point here is this: the cost of the proposed five-year study to understand the impacts of spaceflight emissions and eliminate the risk of an environmental or regulatory surprise that could slow or even stop those spaceflight activities or affect other government activities from astronomy to orbital debris mitigation is a minuscule fraction of the space the economy responsible for spaceflight activities. The proposed effort will, at small cost, eliminate the potential for very costly regulatory overreach or mistakes in the future that could result in performance and budget reduction.

At this juncture, it must be pointed out that this study is not motivated by a stand-alone scientific curiosity. It is designed to be investigative research by collecting necessary data, developing necessary tools and conducting appropriate study, to determine the extent of the Impact, if any, of Spaceflights (an activity for which all the spaceflight stakeholders are responsible) on Earth's Atmosphere: Climate, Ozone, and the Upper Atmosphere. As such the cost of this study should have been built-in in the original funding mechanism of the endeavors. However, since that was not done, the cost of the study should be borne collectively by all spaceflight stakeholders.

Summary

With the emergence of large LEO constellations, expanded lunar and planetary exploration, space tourism, and super heavy lift LNG rockets, an entirely new space industry is fast growing without much consideration or understanding of its environmental effects. The small amount of research and observations done so far lead to the conclusion that the cumulative effects of a vastly larger space industry might be detrimental to climate, stratospheric ozone, and the tenuous upper atmosphere. These effects might have an influence on the work of government agencies such as orbital debris mitigation or astronomical research. If the worst speculative though plausible impacts came to pass, parts of the spaceflight economy could be slowed.

The proposed research is meant as an investment in the future in order to ensure that this does not happen. For an investment less than 0.006% of the economic value of the space economy (let alone the national security) the proposed research can eliminate the major uncertainties and scientific limitations that leave a fast growing and changing industry vulnerable to an environmental disruption. The proposed research

[19] https://spacenews.com/spacex-and-the-categorical-imperative-to-achieve-low-launch-cost/
[20] https://www.nasa.gov/wp-content/uploads/2023/03/nasa-fy-2024-cj-v3.pdf

effort is based on a formula of observation and measurement, modeling and simulation, and scientific assessment to provide information to policy makers. The proposed research was proven out 25 years ago when NASA's Space Shuttle was under pressure for regulation until research removed uncertainties about the environmental impacts of solid rocket motors. We need the same kind of effort today in order to remove doubt that space industry growth might not be sustainable.

As a final key point, the nanoparticles and other disturbances created in the Earth's upper atmosphere due to spaceflight activities have the potential to endure for decades and spark chemical reactions that would destroy stratospheric ozone, which protects Earth from harmful UV radiation. This damage to the environment, which would continue to grow, has the grave potential of harming all livings beings on the planet for generations to come.

II. Major Milestones with Brief Descriptions

Team[21]: Lead, Guide and Advisor: Dr. Surendra P. Sharma, Senior Space Technology Advisor, Exploration Technology Directorate, NASA Ames Research Center ; Dr. Martin Ross, Senior Project Engineer Commercial Launch Projects, The Aerospace Corporation; Dr. Karen Rosenlof , Senior Scientist for Climate and Climate Change, NOAA Chemical Sciences Laboratory, NOAA/CSL; Prof. Chris Maloney, NOAA CSL Chemistry & Climate Processes Group, University of Colorado; Kostas Tsigaridis, University of Columbia; and Dr. Gavin Schmidt, GISS/NASA. This is a team of leading atmospheric scientists, as documented by the brief bios in Appendix I.

Exploratory Study:

Amid growing concerns in the technical, policy, and media communities about the global impact of spaceflight endeavors, Dr. Surendra Sharma, NASA Ames Research Center formed an exploratory work-group and invited Dr. Martin Ross (Aerospace Corporation), Karen Rosenlof (NOAA), and Gavin Schmidt (GISS) to collect the state-of-the-art data on the current understanding of the phenomena, experimental measurements, available modeling tools and published scientific articles.

While researching the availability of credible information about this phenomenon, the exploratory workgroup very well understood that scientific assessment of the impacts of industrial emissions are based on complex models of the global atmosphere. Assessment of spaceflight requires accurate specification of gas and aerosol emissions from launches and reentries at appropriate vertical and horizontal resolution. Such assessment models also require parameterizations of the aerosol, radiative, and chemical processes unique to rocket and reentry emissions.

In an 18-month exploratory study of existing research on the role of "Space Activities" on Earth's climate and atmosphere, our team found that there is a dearth of credible scientific information based on qualified emission data, realistic scenarios of launches and reentry (currently happening) and credible simulation codes. These major knowledge and technological gaps need to be filled. Until that is done, a scientifically proven, credible and reliable assessment of the impact of spaceflight is not possible.

[21] For qualification data on each member see Appendix-I

The Scientific and Technological Gaps:

Assessment models require detailed plume models of launch emissions, based on component emission indexes, scenarios of rocket fleet details, and annual payload projections. Launch emissions are derived indirectly by using the engineering rocket combustion models that emphasize performance over accurate specification of the emissions that are important for atmosphere impacts (NOx, BC (Black Carbon), H_2O, HO_x, PAH (Polycyclic Aromatic Hydrocarbons), CO, CO_2, metal oxides, uncombusted fuel). Existing combustion models use unvalidated representations of complex, altitude dependent, secondary combustion plume processes. Stratospheric plume in situ composition data to validate rocket emission models (e.g., Ross et al., 1999) have not been collected for today's widely used and newly introduced propellants.

Pollution from reentry emissions adds a new dimension to the problem. Data on gas (NO) and aerosol (metals, their oxides, silica, and others) emissions from vaporizing space debris do not yet exist, and a formalism and metrics to describe the impacts from these emissions have not yet emerged. As a consequence, global atmospheric models have not been applied to understand the impacts of reentry emissions.

The Gaps and Needed Fill-in Strategy:

1. **Rocket Plume Intercepts**: In situ measurement of rocket plume chemistry and dynamics are needed to validate far-field plume models and provide input parameters to global models. The NASA WB-57F aircraft, equipped with a variety of instruments that make up the proven NOAA SABRE instrumentation suite, will be flown through rocket plumes between 5 and 120 minutes after launch. The goal is to obtain measurements of plume composition that can be used to infer rocket engine combustion details and the relevant processing of the plume as it expands to model grid scales. Only one instrument (plume lidar) requires new development.
2. **Rocket Plume Remote Sensing:** Remote sensing measurements of rocket plume chemistry and dynamics are needed to validate emission models and provide input parameters to far-field plume models. Multispectral observation of rocket plumes is needed to infer rocket engine emissions. The NASA WB-57F or G-V aircraft can carry flight proven instrumentation such as SAMI (SCIFLI Airborne Multispectral Imager, NASA Langley Research Center, 2024) multispectral imager (LaRC) to obtain data on rocket plume afterburning chemistry and dynamics as a function of altitude for different propellant types.
3. **Reentry Remote Sensing:** Very little is known about how satellites and rocket stages vaporize and recondense particles in mesospheric plumes. Multispectral remote sensing of reentering objects is needed to measure the vertical profile and horizontal extent of reentry destruction and vaporization, particle production, and to validate NASA models of spacecraft demise during reentry. The NASA WB-57F or G-V aircraft[22] can carry the flight proven SAMI (NASA Langley Research Center) to obtain data on reentry vaporization and aerosol production. The data will be used to improve agency models of spacecraft reentry and demise (including those of

[22] https://www.nasa.gov/specials/jsc-aircraft-ops/gulfstream-gv.html

NASA/ODPO, Orbital Debris Program Office) and provide improved input for global atmosphere models.

4. **Reentry Emissions Model Development:** Understanding the atmospheric impact of vapor and aerosol generated during reentry requires emission scenario input data for global atmosphere simulations. The NASA Space Debris Program Office (NASA Johnson Space Center) and space regulatory agencies (FAA and FCC) maintain tools to predict reentry heating, break up, and vaporization and analyze risk but do not include emission profiles. These tools could be improved and modified to predict emission profiles of the type required as input to global simulations. The tools would also be used to plan remote sensing data acquisition (See 3 above) and interpret the multispectral data from the airborne sensors. Numerical tools that could serve as the basis for a reentry emissions model include NASA's Object Reentry Survival Analysis Tool (ORSAT) and ESA's Spacecraft Atmospheric Reentry and Aerothermal Breakup (SCARAB) reentry analysis tools. The present output from these tools would be needed to plan reentry remote sensing campaigns and the data from those campaigns would provide a basis for adding detailed emission predictions.
5. **Middle Atmosphere Global Circulation Models:** Emissions from rockets and reentries accumulate in the middle atmosphere (lifetime of about 4 years) and become entrained in the global stratospheric circulation and so produce the main global impacts. Spaceflight emissions present unique challenges to global models such as accounting for transport of reentry emissions from the mesosphere into the stratosphere, including coupled chemistry and radiation, and cloud nucleation. Comparison of the results of simulation of standard emissions using different models is required to understand impacts with high confidence (e.g., Gunnar et al., 2022). Several different community standard models have been used to analyze rocket emissions including WACCM (Maloney et al., 2022), ModelE (Tsigaridis et al., 2023), and GEOS-Chem (Ryan et al., 2022). These models can be adapted and used in a coordinated way with standardized emission scenarios to understand launch and reentry emissions with a view to the different domains, strengths, and weaknesses of each model.
6. **Upper Atmosphere Global Circulation Models:** The fact that as much as 25% of a rocket's propellant is burned in the thermosphere is not widely appreciated. Spaceflight emissions into the thermosphere are readily seen from ground long after launch. Indeed, twilight launch plumes, bright reentry plumes, and post-launch regional airglows are frequently reported by the public. These visual displays will, at some level of spaceflight activity, affect ground-based astronomy as much as the satellites they launch do (Hasan, 2023). Thermospheric impacts including airglow, ionospheric holes, and high-altitude cloudiness are an increasing area of concern as spaceflight plays an increasing role as part of the space weather background.
7. **Upper Atmosphere Plume Remote Sensing:** Thermospheric impacts including airglow, ionospheric holes, and high-altitude cloudiness, generally "space weather", are also an increasingly active area of research and spaceflight will play an increasing role in advancing that research. These perturbations are large enough that they can been seen by the naked eye in the days following launch (Stevens et al., 2012). These molecular emissions and high-altitude cloud formations and ionospheric "holes" (Chenegor, 2022) present important signatures of the impact of rocket emissions in the thermosphere. These visible and wide area coverage emissions could at some level of space activity become an interference for ground-based astronomy.
8. **Laboratory Studies of Critical Processes:** Many physical, chemical, and hardware focused process that are critical to understanding of the impacts of launch and reentry emissions can only be understood by laboratory measurements. These include investigations of natural and spaceflight

aerosols and measurement of rocket engine emissions in order to provide actual inputs to plume chemistry models. Highest priority measurements include changes in sulfate aerosol properties caused by metallic inclusions from reentry emissions, measurement of rocket engine exit plane exhaust composition at test stands, and chemical rate constants for specific reactions.

9. **Representative Emissions Pathways Development:** The space industry's rapid growth and development and the demands for data and input demands from the modeling and measurement planning activities requires the development of standard ways of specifying space industry emissions. This is similar to the IPCC (Intergovernmental Panel on Climate Change) specification of GHG (Greenhouse Gases) emissions to enable model intercomparison and exploration of policy options. The same needs to be done for spaceflight by different propellant, reentry, launch vehicle, constellation size, space debris mitigation, GEO and MEO systems, and lunar and planetary options.

White Paper:

A white paper describing the scientific and technological gaps and a research plan to resolve them and develop the tools for comprehensive assessment of the impact of Spaceflights on Planetary Atmospheres and Climate was co-authored by all team members. A copy of this paper is attached in Appendix-II.

III. Additional Contributions from Team Members

Spaceflight Emissions Inventory and Specification: Dr. Martin N. Ross:

1. A white paper "Impacts of Spaceflight on the Global Atmosphere: Current Understanding, Knowledge Gaps, NASA's Role, and Roadmap Forward was written. The document serves as a description of the SOA (service-oriented architecture), gaps in scientific knowledge, and research that is required to make progress. The document was widely distributed within the science community and serves as a draft manuscript for publication.
2. An article "Staying Ahead of the Space Sustainability Curve" was written for the AIAA (American Institute of Aeronautics and Astronautics) magazine Aerospace America. This was a summary of the white paper but was not published as planned due to internal clearance issues at The Aerospace Corporation. (Internal reviewers at Aerospace deemed it a "news article" because it was not formally peer reviewed at a time when the company had instituted a temporary ban on such publications. The manuscript is being rewritten for publication in "Perspectives of Earth and Space Scientists" which is a peer reviewed AGU (American Geophysical Union) publication.
3. Analysis to define future spaceflight emission scenarios was performed based on known changes in the space industry (e.g., large LEO constellations and transition to LNG propellant) and expected growth. The results were presented at AIAA SciTech (2023 and 2024) and AMS (American Meteorological Society; 2022). A manuscript describing the derivation of these scenarios for publication in IEEE (Institute for Electrical and Electronics Engineers) J. Space. Safety and Engineering is in work.
4. Supported the modeling work of Maloney et al. (2024) and Tsigaridis et al. (2024) by providing the emission scenario specification for simulations of the impacts of future launch and reentry
5. Supported a wide variety of briefings, seminars, and interagency discussions in order to organize and direct NASA research (including interagency cooperation) into spaceflight emissions. This

includes presentations to NASA and NSF to prepare the groundwork for the anticipated national workshop and serving as Convener for the 2024 AGU session on spaceflight emissions.

<u>Simulation of Gaseous and Aerosol Composition (Surface to Stratopause): Dr. Kostas Tsigaridis/Dr. Gavin Schmidt:</u>

Methods

We have been using the GISS ModelE Earth system model with prognostic gaseous and aerosol composition including aerosol microphysics, which extends from the surface to the stratopause (about 65 km in altitude). In parallel, the CESM WACCM (Community Earth System Model : Whole Atmosphere Community Climate Model) model performed similar simulation with ours, which we are using to understand the robustness of our results across models. We made two sets of experiments: one that essentially replicated the work from Maloney et al. (2022), and one where we used newly-generated emissions profiles by Martin N. Ross to study rocket propellant emissions under plausible launch scenarios in the 2050s. For the latter case we assumed both 1k and 10k heavy launches per year, and studied the impact of emitted CO, NO_x, water, and BC, both separately and combined, for launches from the US (Cape Canaveral) and New Zealand (Māhia).

Key results

GISS ModelE qualitatively compares extremely well against the effects calculated by CESM, which provides confidence about the robustness of the model's output. Both models agree that it is BC the species that dominates the response, with the other species showing either marginal or no signal to climate impacts. Both models also show that tropopause warming weakens the cold trap and allows water to leak from the troposphere in to the stratosphere, where it modifies ozone chemistry and leads to ozone depletion. Quantitatively ModelE shows a stronger impact of BC to the tropopause temperatures compared with CESM, which leads to a stronger water leakage into the stratosphere. A paper about this is being prepared for publication. Results from ModelE show that the launch location (US or NZ) plays an important role on the hemispheric asymmetry of the resulting composition change, which affects climate asymmetrically, but on the global scale the signal is practically the same.

Work underway

Reentry emissions from burning satellites will be simulated, by including alumina particles in the model. As a starting point these would resemble sulfate, since the sulfate and alumina optical properties are not that different from each other, but separate optical properties will be used later in the project. We will also compare the effects of kerosene and LNG-fueled rockets for future payload-focused scenarios. This will account for the bigger payloads that LNG 'super-heavy' rockets are expected to have. The change in stratospheric dynamics is also currently under study, and we plan to hire a NASA intern to further pursue this during the spring 2025.

<u>Satellite Reentry: Dr. Christopher Maloney/Dr. Karen Rosenloff:</u>

Project Overview and Summary:

Methods: We simulated a projected annual emission of 10 Gg/yr of satellite reentry aerosol in the NCAR WACCM (NSF, National Center for Atmospheric Research; Whole Atmosphere Community Climate Model) model. WACCM was coupled with a sectional microphysical model, CARMA (Consortium for the Advancement of Research Methods and Analysis), in order to allow us flexibility in representing the possible aerosol size distributions produced via satellite reentry kinetics. We also assumed that reentry material would be mainly composed of aluminum oxide (Al_2O_3). Reentry Al_2O_3 was emitted between 60km and 70km, the altitude range where satellite ablation vapors begin to cool and coalesce. Two separate aerosol size distributions were simulated in an attempt to represent the uncertain size of aerosol produced by satellite ablation processes. The smaller size distribution ranged from 0.01 µm to 1.7 µm in size while the larger aerosol size distribution ranged from 0.1 µm to 17 µm. In addition, four separate satellite reentry locations were investigated: 1) Uncontrolled reentry into mid-latitude bands (40^0 N/S-80^0 N/S), 2) Controlled reentry into the equator region (20^0 S-20^0 N), 3) Controlled reentry at the south pole (80^0 S-90^0 S), and 4) Controlled reentry into the South Pacific Uninhabited Area (SPOUA, 41^0 S-46^0 S). Each of these scenarios assumed that all of 10 Gg/yr aerosol emissions occurred within the specified region. Lastly, the Al_2O_3 aerosol emitted into the WACCM/CARMA model was allowed to only react with the radiative transfer code. We are still developing a newer version of the CARMA model which can properly represent the heterogeneous chemistry that may be associated with Al_2O_3 in the stratosphere.

Results: We found that reentry alumina accumulates at high latitudes in both hemispheres between 10km and 30km. The time that it takes for this accumulation to occur ranges from several months to up to 2 years and depends on both aerosol size distribution and reentry location. Small changes in heating rates near the stratopause lead to as much as 1.5 K temperature anomalies in the mesosphere and stratosphere at high latitudes. Numerous reentry scenarios experienced a 10% reduction in the southern hemisphere polar vortex wind speed. The weakened southern hemisphere polar vortex is accompanied by a wintertime/springtime warming of the stratospheric south pole. A 3%-6% reduction in polar stratospheric clouds and a 3-9 DU (Dobson unit) increase in the column ozone concentration also occur in the south pole region during these seasons. Conversely, two reentry patterns, the equatorial and mid-latitude reentry scenarios that emitted small aerosol, experienced a statistically significant strengthening of the northern hemisphere polar vortex. As a result, these two reentry scenarios were the only two to have a 1 K cooler wintertime polar stratosphere, as well as a 3 DU reduction in column ozone at the north pole.

When comparing the overall climate impacts of the various reentry scenarios investigated in this study, we found that reentry location and aerosol size distribution play a significant role in the climate response from a radiative transfer perspective. Most importantly, we found that low latitude reentry locations (i.e. equatorial and SPOUA) may have a larger climate impact than high latitude emission patterns.

IV. Publications, Presentations and Outreach by Team Members

Publications:

- A manuscript titled "Investigating the Potential Atmospheric Accumulation and Radiative Impact of the Coming Increase in Satellite Reentry Frequency" has been submitted to Journal of Geophysical Research and is currently under review. Authors: **Christopher M. Maloney**, Robert W. Portmann, Martin N. Ross, & Karen H. Rosenlof.
- An extended abstract titled "Stratospheric loading and radiative impacts from increased Al_2O_3 emissions caused by an anticipated increase in satellite re-entry frequency" was published in the conference proceedings of the 2024 AAIA SciTech Forum (https://doi.org/10.2514/6.2024-2169). Authors: **Christopher M. Maloney**, Robert W. Portmann, Martin N. Ross, Karen H. Rosenlof, & Charles G. Bardeen.

- **Tsigaridis, K.**, R. Field, S.E. Bauer, M.N. Ross, C. Maloney, G.A. Schmidt, and K.H. Rosenlof, 2024: Composition and climate impacts of increasing launches to Low Earth Orbit. In AIAA SciTech 2024 Forum, 8-12 January 2024, Orlando, FL, American Institute of Aeronautics and Astronautics, doi:10.2514/6.2024-2168.

Presentations:

- **C.M. Maloney**, R.W. Portmann, M.N. Ross, & K.H. Rosenlof (January, 2023). AMS Annual Meeting (oral presentation), title: "Potential Stratospheric Impacts of Increased Emissions due to Space Traffic".
- **K. H. Rosenlof**, Processes and Analogs (November 2023). Earth's Radiation Budget Science Meeting (invited overview presentation), (https://csl.noaa.gov/research/erb/meetings/202311/).
- **C. M. Maloney**, R.W. Portmann, M.N. Ross, K.H. Rosenlof, & C.G. Bardeen (January, 2024). AAIA SciTech Forum (oral presentation), title: "Stratospheric loading and radiative impacts from increased Al_2O_3 emission caused by an anticipated increase in satellite re-entry frequency".
- **K. H. Rosenlof** (January 2024). AAIA SciTech Forum (technical panel presentation), title: "Overview of the Space Industry Emissions Research in NOAA's Radiative Budget Initiative".
- **G. A. Schmidt**, K. Tsigaridis, C.M. Maloney, M.N. Ross, R. Field, K.H. Rosenlof, R.W. Portmann, & S.E. Bauer (January 2024). European Space Agency workshop on space travel emissions (oral presentation), title: "Modeling the impacts of launch emissions and orbital debris re-entry: Initial findings and need for observational constraints".
- **C. M. Maloney**, R.W. Portmann, M.N. Ross, & K.H. Rosenlof (February, 2024). AMS Annual Meeting (oral presentation), title: "Modeling the atmospheric transport and possible radiative impact of alumina aerosols emitted from the projected increase in annual satellite reentry emissions".
- **K. H. Rosenlof** & C.M. Maloney (April, 2024). European Geosciences Union General Assembly (oral presentation), title: "Potential impacts of launch and orbital debris re-entry emissions".
- **K. H. Rosenlof & G.A. Schmidt** (May 2024). AdHoc Working Group: Atmospheric Impact of Spacecraft Reentry, title: "US plans for atmospheric reentry".
- **C.M. Maloney**, R.W. Portmann, M.N. Ross, & K.H. Rosenlof (June, 2024). AMS Middle Atmosphere Conference (poster presentation), title: "The Potential Impact of Increased Satellite Reentry Emissions Upon Earth's Middle Atmosphere".
- **C.M. Maloney**, R.W. Portmann, M.N. Ross, & K.H. Rosenlof (July, 2024). Quadrennial Ozone Symposium (poster presentation), title: "The Potential Impact of Increased Satellite Reentry Emissions Upon Earth's Middle Atmosphere and Ozone".
- **K.H. Rosenlof**, C.M. Maloney, & M.N. Ross (July, 2024). Quadrennial Ozone Symposium (oral presentation), title: "Rocket launches and satellite reentry: Initial findings and the need for observational constraints given projections of a rapidly increasing number of low earth orbit large satellite constellations".
- **K.H. Rosenlof,** C.M. Maloney, E. Bednarz, & M.N. Ross (September 2024). The Royal Society of Chemistry's Desktop Seminar Series (invited presentation), title: "Possible Future Threats to the Ozone layer".
- Dr. Maloney will present the published satellite reentry study results at the upcoming AGU 2024 Fall Meeting and the 2025 AMS Annual meeting.

- We are in the process of developing an updated version of the CARMA aerosol model that will be able to properly represent the stratospheric heterogeneous chemistry that will occur on alumina. Once complete, we plan to re-run these simulations with the more complex model and publish the new results.
- **Tsigaridis, K.**, R. Field, S.E. Bauer, M.N. Ross, C. Maloney, G.A. Schmidt, and K.H. Rosenlof, 2024: Composition and climate impacts of increasing launches to Low Earth Orbit. In AIAA SciTech 2024 Forum, 8-12 January 2024, Orlando, FL, American Institute of Aeronautics and Astronautics, doi:10.2514/6.2024-2168.
- **Tsigaridis, K.**, 2024: The complex role of rocket launches on stratospheric warming, dynamics, and chemistry. In AIAA SciTech 2024 Forum, 8-12 January 2024, Orlando, FL, American Institute of Aeronautics and Astronautics.
- **Tsigaridis, K.**, R. Field, S. E. Bauer, G. A. Schmidt, C. Maloney, K. Rosenlof, 2024: The future chemistry and climate impacts of large, fully-reusable methane-fueled rockets, in AGU fall meeting, December 2023, San Francisco, CA, USA.
- Tsigaridis, K., R. Field, **S. E. Bauer**, G. A. Schmidt, C. Maloney, K. Rosenlof, 2024: The future chemistry and climate impacts of large, fully-reusable methane-fueled rockets, in AMS meeting, January 2024, Baltimore, MD, USA.
- **G.A. Schmidt**, K. Tsigaridis, C.M. Maloney, M.N. Ross, R. Field, K.H. Rosenlof, R.W. Portmann, & S.E. Bauer (January 2024). European Space Agency workshop on space travel emissions (oral presentation), title: "Modeling the impacts of launch emissions and orbital debris re-entry: Initial findings and need for observational constraints".
- **K.H. Rosenlof & G.A. Schmidt** (May 2024). AdHoc Working Group: Atmospheric Impact of Spacecraft Reentry, title: "US plans for atmospheric reentry".
- K. Tsigaridis, **C. Maloney**, M. Ross, R. Field, S. Bauer, G. Schmidt, K. Rosenlof, R. Portmann (June 2024). AMS Middle Atmosphere Conference (poster presentation), title: "The Stratospheric Response to Increased Rocket Launch Emissions"
- K. Tsigaridis, **C. Maloney**, M. Ross, R. Field, S. Bauer, G. Schmidt, K. Rosenlof, R. Portmann (July 2024). Quadrennial Ozone Symposium (poster presentation), title: "The Stratospheric Ozone Response to Increased Rocket Launch Emissions"

Outreach

- **Kostas Tsigaridis** was interviewed by Discover magazine on the subject of rocket fuels and their environmental impact, May 16, 2024, published May 22, 2024. https://www.discovermagazine.com/the-sciences/the-rocket-fuel-of-the-future-may-be-more-environmentally-friendly.
- **Kostas Tsigaridis** was interviewed by the German public radio (Deutschland Radio) on the topic of his AGU 2023 oral presentation about rocket launches and their impact on future climate, Dec 18, 2023, broadcasted Feb 20, 2024: https://www.deutschlandfunk.de/russ-und-wasser-wie-raketenstarts-die-atmosphaere-belasten-dlf-785f7bd6-100.html (in German).
- **Kostas Tsigaridis (invited)**, Robert Field, Susanne E. Bauer, Christopher Maloney, Gavin A. Schmidt, Karen H. Rosenlof, and Martin N. Ross (2024), Limitations and challenges in modeling the atmospheric impacts of space flight, AGU fall meeting.
- **Martin Ross** has been interviewed by The New York Times, The Wall Street Journal, The Washington Post, and Space News regarding rocket launch and reentry impacts and future research requirements.

V. Workshop (Spring 2025): The Impacts of a Growing Space Industry on Earth's Atmosphere- Research Challenges and Opportunities

Motivation:

As the previous discussions suggest, this phenomenon (Impacts of a Growing Space Industry on Earth's Atmosphere) is complex, and the technical community needs to engage and consult a broader community of experts, thinkers, planners, researchers, and technologists in order to determine the level and course of research that could be carried out to resolve these questions. With this goal the team has proposed and is planning to hold a workshop, "The Impacts of a Growing Space Industry on Earth's Atmosphere- Research Challenges and Opportunities," sometime in Spring 2025.

It will be organized by the national Academies of Science [Atmospheric Sciences and Climate Space Studies Board]. The cost incurred will be shared equally by NOAA, NASA and NSF ($ 100 K each).

Workshop Participants:

Researchers at academic and government organizations
Representatives from regulatory agencies (FCC, FAA, Department of Commerce)
Representatives from commercial space
Other key stakeholders (DoD, ESA, Office of Science and Technology Policy, International Astronomical Union)

Workshop Outcomes:

A. Increased awareness of the wide range of spaceflight impacts among participants.
B. Review of the scientific state of the art and identification of important knowledge gaps
C. Review the information needs of regulatory and science agencies.
D. Recommendations for research directions to close knowledge gaps
E. Final Report

VI. Outreach to NASA HQ Senior Leadership

Early this year Dr. Surendra Sharma started an outreach and advocacy campaign to let the NASA senior leadership be aware of the importance of Impacts of a Growing Space Industry on Earth's Atmosphere and our comprehensive multi-year multi-agency plan to fill all the technological and knowledge gaps in its understanding. The Earth Science management facilitated several presentations to the senior management of Science Mission Directorate, Office of Technology, Policy & Strategy (OTPS) and NASA Chief Scientist's office regarding this proposal. OTPS, taking notice of study's importance, organized a series of group meeting.

After 6+ hour-long meetings, discussing various aspects of the proposal and with very active idea exchange, it was decided that a memo to the NASA top leadership will be drafted requesting guidance and advice. Such a memo was drafted and submitted on July 12, 2024.

VII. Outreach and Communications with External Collaborators, In-Kind Supporters and other Activities [Led by Dr. Surendra Sharma]

External Partners:

- **National Science Foundation:**
  In late 2022, Dr. Sharma was approached by the Special Advisor for Spectrum, National Science Foundation to seek advice related to a SpaceX-NSF collaboration on Radio Frequency spectrum-coexistence studies. Later on, SpaceX StarLink's request was expanded to additional collaboration with NSF to quantify alumina production that occurs during spacecraft reentry.

  Realizing that NSF has a collaborating relationship with Space-X, in mid-2023, Dr. Sharma initiated dialogues with various NSF managers (especially in the Climate and Large-Scale Dynamics Program) , in search for research funding for our study. We contacted various managers in the Atmospheric and Geospace Sciences Division in the following programs:

  a. Atmospheric Chemistry Program: Advance knowledge of the impacts of spaceflight emissions on climate and ozone
  b. Atmospheric Chemistry Program: Advance understanding of the impact of spaceflight emissions on climate and ozone
  c. Geospace Section: Aeronomy Program: advance understanding of the impact of spaceflight emissions on mesosphere, thermosphere, and ionosphere

  We plan continue our dialogue to expand our partnership with NSF managers. At this point, it must be pointed out that NSF has already promised $ 100 K (in FY 25 funds) towards the workshop, we are planning.

- **Earth Radiation Budget:**
  At the direction of Congress in 2020, NOAA is leading a multi-year research initiative to investigate natural and human activities that might alter the reflectivity of the stratosphere and the marine boundary layer, and the potential impact of those activities on the Earth system. The NOAA Earth's Radiation Budget (ERB) Initiative aims to:
  - Improve the understanding of aerosol impacts on the Earth's energy balance.
  - Establish a capability to observe and monitor stratospheric conditions.
  - Detect and accurately simulate the impacts of natural and human-caused aerosol injections on radiative forcing, weather, climate, and the Earth system;

- Apply this improved foundational understanding to Earth system prediction.

Current (FY 2024) ERB for NOAA is approximately $6.72B. Its SABRE mission, whose goal is to significantly advance our understanding of the present day composition, chemistry, and dynamics of the stratosphere and their impacts on the climate system, has plans for second test flights: January - February 2025, Ellington Field (EFD), Houston, Texas.

Dr. Sharma had numerous sessions with NOAA ERB managers about our participation in this flight experiment.

- **Collaboration with ESA**:
  A sustainable development *expert at CNES (*French Space Agency*)*, on behalf of ESA, approached us for a possible collaboration in our work on rocket launch emissions etc. We informed NASA leadership that we are in contact with ESA management. We started a process of communication with a group of prominent experts from ESA in late 2022 and had another discussion meeting on April 26, 2023, to chart out an agenda for this collaboration. Once we have a framework of collaboration, we will pass on that information to appropriate authorities. An ad-hoc working group has been organized by ESA on the impacts and part of the working group on this aspect of space sustainability at NASA HQ. Two of our team members are members of this group.

  The Other ESA Connection:
  Dr. Sharma, as the chair of AIAA Space Exploration Integration committee and Topic Administrator for SciTech 2023 organized an international discussion panel on "Perspectives on Space Exploration." After the conference, we reached out to the DC based Head of the ESA Washington Office to work in future on joint AIAA sessions and other activities.

- **Congressional Inquiry:**

  Around July 2022, NASA Public Affairs office received an inquiry:

  " if NASA has any plans in place to regulate commercial space travel pollution and to inquire about NASA's thoughts on researchers' finding that "routine space tourism launches may undermine progress made by the Montreal Protocol in reversing ozone depletion in the Arctic springtime upper stratosphere.."

  A group of scientist and managers at NASA HQ (Dr. Sharma included) formulated the following response from NASA for public release:

  "Rocket launches can cause impacts on local atmospheric composition along the launch vehicle's trajectory depending on the type of propellant used to fuel the rocket. Compared to other human activity, the impact of rocket launches is small today, though we recognize that the number of launches has been increasing over time. Although NASA is not a regulatory agency, we observe and analyze changes in the Earth system, including the atmosphere, and we'll continue to follow future analyses of the impacts of rocket launches as well as monitor impacts on climate on through Earth science missions."

VIII. Special Sessions Organized at Prominent Conferences

- **AIAA SciTech 2025, January 6-10, Orlando, FL.**
  Space Exploration; Topic Admin: Dr. Surendra P. Sharma
  Technical Paper Presentation (120 min)
  Impact of Space Activities on Climate and Atmosphere; 1/10/2025.
  Chairs: Dr. Mark Benton (Chair) | José Ferreira (Co-Chair)

  1. A case study of international collaboration space missions for combating global climate change: strategic and technical perspectives; Sundararajan, Venkatesan
  2. Latitudinal Dependency of Satellite Propulsive Emissions Deposition in the Lower Thermosphere; Jia-Richards, Oliver
  3. Spatial and Temporal Modelling of Spacecraft Demise upon Reentry from Low-Earth Orbit: Ferreira, José
  4. Cis-Lunar Surveillance System Technological and Strategic Perspectives. Thangavelautham, Jekan
  5. Evaluating Disposal and End-of-Life Strategies for Cislunar and Lunar missions to Enable Sustainable Exploration; Nassif, Mohamed

- **AGU24, Dec. 9-13, 2024, Washington DC**
  Talks for eLightning (9 three minute presentations): Conveners: Dr. Martin N. Ross, Dr. Karen Rosenloff, Dr. Jack Kaye and Dr. Surendra P. Sharma

  1. Anthropogenic mass loading of metals in the upper atmosphere due to space activities (Boley et al.) calculation of metallic emissions from UBC group
  2. Decadal Scale Influences of Space Traffic on Polar Mesospheric Cloud Frequency (Mukherjee et al.) historical PMCs; NRL group
  3. Fast-Reponse In Situ Measurements in Rocket Plumes: An Unexploited Tool for Studying Dynamics and Chemistry in the Lower Stratosphere (Toohey) Darin's uber fast data from space shuttle plume; CU
  4. (Invited) Limitations and challenges in modeling the atmospheric impacts of space flight (Tsigaridis et al.)
  5. Recent Observations of Rocket Exhaust Effects on the Ionosphere (Baumgardner et al.) Ionospheric holes; Boston group
  6. Rocket Emissions and Their Environmental Footprint: A Study of 2050 Scenarios (Pradhan et al.) Don Wuebbles group for FAA; models
  7. Satellite ion-engine thruster emissions and the potential to interact with the ionosphere (Jain et al.) MIT group, LEO ion drive emissions.
  8. In situ observations of a kerosene-fueled rocket plume sampled during SABRE 2023 (Thornberry et al.) SABRE data.
  9. (Invited) Impacts of Spacecraft Reentry on the Stratosphere (Murphy et al.)

- **AIAA SciTech 2024, January 8-12, Orlando, FL;**
  Space Exploration; Topic Admin: Dr. Surendra P. Sharma
  Technical Paper Presentation (120 min.)
  Impact of Space Activities on Climate and Atmosphere, 1/11/2024.
  Chairs: Dr. Karen Rosenlof - NOAA; Dr. Martin N. Ross

  1. Space Sustainability: A Circular Approach to Mitigating Environmental Impacts; Jones, Karen
  2. Composition and Climate Impacts of increasing launches to Low Earth Orbit; Tsigaridis, Kostas
  3. Stratospheric loading and radiative impacts from increased Al_2O_3 emission caused by an anticipated increase in satellite re-entry frequency; Maloney, Christopher
  4. Future Space Industry Emission Scenarios; Ross, Martin

  Technical Discussion Panel (120 min.)
  Impact of Space Activities on Climate and Atmosphere-Discussion, 1/11/2024.
  Moderators: Dr. Ross, Martin N. Ross; Dr. Karen Rosenlof - NOAA

  Speakers:
  1. Jeetendra Upadhyay; Office of Environment and Energy - Emissions Division (AEE-300); Federal Aviation Administration.
  2. Sebastian Eastham; Principal Research Scientist; Joint Program on the Science and Policy of Global Change; MIT Center for Global Change Science.
  3. Prof. Don Wuebbles; University of Illinois.
  4. Martin Ross; Research Scientist; The Aerospace Corporation.

- **AIAA SciTech 2023, January 23-27, National Harbor, MD ;**
  Space Exploration; Topic Admin: Dr. Surendra P. Sharma

  Technical Discussion Panel (240 min.)
  Impact of Space Endeavors on Earth's Climate and Atmosphere, 1/27/2023.
  Moderator: Dr. Karen Rosenlof - NOAA

  Panelists:

  1. Karen Rosenlof ; NOAA
  2. Martin Ross ; The Aerospace Corporation
  3. Karen Jones ; The Aerospace Corporation
  4. Gavin Schmidt ; GISS
  5. Sebastian Eastham
  6. Darin W Toohey ; University of Colorado
  7. Al Tadros ; Redwirespace

Appendix-I

[Brief Qualification Narrative of the Team members]

Dr. Martin N. Ross:

Dr. Martin N. Ross is a renowned climatologist/scientist with Commercial Launch Projects at The Aerospace Corporation. In this role, Ross conducts research concerning climate change and the impacts of space systems on the global atmosphere. He works with the National Oceanic and Atmospheric Association (NOAA), the National Aeronautics and Space Administration (NASA), and other organizations to study how rocket launches, and space debris reentry affect Earth's climate and stratospheric ozone layer.

In 1997, Ross led a national group of researchers who obtained the first measurements of rocket plume ozone holes and their impact on global ozone. He subsequently led the NASA/NOAA/USAF ACCENT program between 1998 and 2003. He is currently developing new strategies and studies to understand how the space industry can grow and innovate in a globally sustainable manner.

Dr. Christopher Maloney:

Dr. Christopher Maloney is a Research Scientist II at the Cooperative Institute for Research in Environmental Sciences at the University of Colorado, Boulder, as well as a member of the Chemistry & Climate Processes group in the NOAA Chemical Sciences Laboratory. Dr. Maloney's expertise is in modeling clouds and aerosols in general circulation models. His current area of focus includes the impact of space travel related emissions on Earth's middle atmosphere, as well as climate effects from the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption. In addition to these topics, Dr. Maloney is part of a collaborative effort with the National Center for Atmospheric Research to develop a new version of the sectional microphysical aerosol model, CARMA(Community Aerosol and Radiation Model for Atmospheres), that can represent more exotic aerosols, such as those released during satellite reentry. In addition to research, Dr. Maloney serves on the American Meteorological Society's planning committee for the Early Career Leadership Academy. He also maintains the general circulation model for his research group at NOAA, and he serves as the high-performance computing portfolio manager for the entire NOAA CSL laboratory.

Dr. Karen Rosenloff:

Dr. Karen Rosenloff is a Senior Scientist and Group Leader for the Chemistry and Climate Processes program at the NOAA Chemical Sciences Laboratory. Karen's primary focus is on understanding how the stratosphere will change with increasing greenhouse gases, and what the impacts are on surface climate, using model output, satellite measurements, ground-based measurements and data collected during high altitude aircraft experiments to understand stratospheric processes. Her scientific impact is evident in both her leadership of chemistry and climate processes, and her research of stratospheric dynamics, stratosphere-troposphere interactions, and stratospheric composition including water vapor, ozone, and aerosols.

Karen is a Fellow of the American Geophysical Union (AGU).

Dr. Kostas Tsigaridis:

Kostas Tsigaridis is a Research Scientist at Columbia University and NASA GISS. A chemist by training, has a broad expertise related with atmospheric composition, both gaseous and particulate, as well as the climate impacts of atmospheric composition changes impacts on climate. Furthermore, he is interested in biogeochemical cycles, and in general in understanding how different Earth compartments (atmosphere, terrestrial and marine biosphere, cryosphere, climate) interact as a big system. He is a key model developer of GISS ModelE, the NASA climate and Earth system model.

Dr. Gavin Schmidt:

Gavin Schmidt is the lead for the GISS Earth System Model and is focused on ensuring that we can use the most accurate and appropriate inputs for the model and making sure that the model contains the key processes that can lead to impacts. He is on the ad-hoc working group led by ESA on the impacts and part of the working group on this aspect of space sustainability at NASA HQ.

Dr. Surendra P. Sharma:

Dr. Surendra Sharma, an internationally renowned authority on nonequilibrium phenomena in hypersonic flows, has advanced the state-of-the-art in this field of the research and applications related to reentry physics. Dr. Sharma established the Reentry Physics Simulation Facility (only 4-5 such facilities exist in the entire world), which then produced precise and comprehensive experimental data (spectrally resolved radiation emission data and thermochemical reaction rates) to build/validate mathematical models of hypersonic atmospheric flight. The models used today in simulations of hypersonic Earth atmospheric flight are testament to his untiring efforts. Furthermore, the models have been successfully validated against flight data (FIRE II, Hash *et al.*, 2007) and have been/are being used in numerous missions, including, Space Shuttle Orbiter, X-33, X-34, X-37, Stardust, Orion, OSIRIS-REx, Commercial Crew, Dragonfly, Mars Sample Return, SDIO, BMDO and Skipper bow-shock spacecraft.

Furthermore, the facility established by Dr. Sharma for Earth atmospheric flight also finds applications to several upcoming NASA missions to Mars and the outer planets.

For the last decade and a half, primarily, Dr. Sharma has been acting as advisor to the senior leadership of Advanced Exploration Systems (now re-organized and merged into other divisions), ESDMD on key space exploration technologies to enable sustained human presence in cis-lunar space and beyond, without doing any harm to the environment of the planet we live on or the planets we visit in the future.

Dr. Sharma is a Fellow of AIAA.

Appendix-II

Impacts of Spaceflight on the Global Atmosphere:

Current Understanding, Knowledge Gaps,
NASA's Role, and Roadmap Forward

Martin Ross
The Aerospace Corporation

Karen Rosenlof
NOAA Chemical Sciences Laboratory

Gavin A. Schmidt
Director, NASA Goddard Institute for Space Studies

Jack Kaye
Research Director, Earth Science Division, NASA HQ

Surendra Sharma
Senior Space Technology Advisor, NASA Ames

September 23, 2024

Executive Summary: There are growing concerns in the technical, policy, and media communities about the global impact of spaceflight endeavors. In response, NASA formed an exploratory working group to gather relevant information about current scientific expertise, evaluate key knowledge gaps, and chart a strategy in order to close the gaps and properly assess spaceflight's impacts. This 2 year-long study, supported by NASA's internal funds and likely to continue in 2023, found major gaps in data and modeling capabilities which need to be overcome before the impacts of the space industry can be credibly assessed.

This white paper describes these gaps and a research plan for comprehensive assessment. It should be noted that the new plan represents a significant increase from this small exploratory effort supported by internal funds and that a multi-agency augmented funding structure is noted.

A. Background

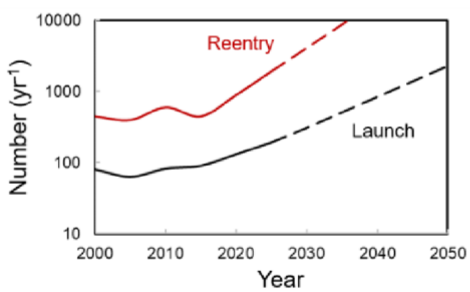

Figure 1. Historical (solid) and predicted (dashed) global launch and large (0.25 t) object reentry rate according to scenarios of space development that include LEO megaconstellations, cis-lunar development, human exploration, and increased MEO utilization.

Spaceflight activities represent a unique source of gasses and particles that are emitted into every layer of the atmosphere (Ross and Jones, 2022). Rocket launch and space debris reentry vaporization emissions into the middle atmosphere (stratosphere and mesosphere, 10-85 km) impact global climate and stratospheric ozone. Launch emissions in the thermosphere do not affect climate but have potentially long term changes in upper atmosphere cloudiness, airglow, and electron content (Chou et al., 2018). It has generally been assumed that spaceflight emissions are small, with minimal global impacts, even given a low level of scientific understanding (WMO, 2022). However, at significantly increased levels of spaceflight activity the assumption of minimal impacts may no longer be true.

In fact, the space industry has entered a new era of accelerating growth and technology innovation (Miraux, 2022). Emissions from new and very large rockets, using new propellants, are expected to sharply increase, especially in the mesosphere and lower thermosphere (Ross and Toohey, 2019). The emergence of massive LEO constellations means that emissions from space debris reentry vaporization will become a significant, perhaps dominant, source of middle atmosphere aerosol (Byers and Boley, 2021). See Fig 1.

Global simulations of rocket emissions have been done occasionally (Danilin et al., 2003; Maloney et al., 2022); simulations of reentry emissions and far-field plume evolution have not been done at all. In situ measurements of rocket emissions were last done over twenty years ago (Ross et al., 1999). Current NASA funded work is improving rocket emission scenarios and generating the first models of the impacts of methane fueled rockets. There is little doubt, however, that the current scientific understanding of spaceflight emissions is not at all consistent with the anticipated increase of those emissions.

A mini exploratory research group was organized by Surendra Sharma, ECD, ESDMD, NASA (20172023) in early 2022 with Martin Ross (The Aerospace Corp.), Gavin Schmidt (GISS,, NASA) and Karen Rosenlof (NOAA) as participants to gather data and study this impact on the climate. This activity is being supported by Earth Sciences Division, SMD, NASA. The study found major gaps in data and modeling capabilities which need to be overcome before the impacts of the space industry can be credibly assessed. The gaps and the needed step-up activities are described below.

B. Knowledge Gaps

Scientific assessment of the impacts of industrial emissions are based on complex models of the global atmosphere. Assessment of spaceflight requires accurate specification of gas and aerosol emissions from launches and reentries at appropriate vertical and horizontal resolution. Such assessment models also require parameterizations of the aerosol, radiative, and chemical processes unique to rocket and reentry emissions.

Assessment models require detailed plume models of launch emissions, based on component emission indexes, scenarios of rocket fleet details, and annual payload projections. Launch emissions are derived from engineering rocket combustion models that emphasize performance over accurate specification of the emissions that are important for atmosphere impacts (NO_x, BC, H_2O, HO_x, PAH, CO, CO_2, Al_2O_3). Existing combustion models use unvalidated representations of complex, altitude dependent, secondary combustion plume processes. UTLS plume in situ composition data to validate rocket emission models (e.g., Ross et al., 1999) have not been collected for today's widely used and newly introduced propellants.

Interest in reentry emissions is new. Models of gas (NO) and aerosol (metals, their oxides, silica, and others) emissions from vaporizing space debris have not been constructed and a formalism and metrics to describe the impacts from these emissions have not yet emerged. As a consequence, global atmospheric models have not been applied to understand the impacts of reentry emissions.

As with cirrus contrails from jet engines, important chemical and aerosol processing occurs as rocket and reentry emissions diffuse from plume scales (10 m) to global model grid scales (10^5 m). Such far-field plume models (stratosphere, mesosphere, and thermosphere) need to be developed in order to bridge the gaps in time and distance scales from emissions to filling global model grid elements.

Assuming availability of authoritative global atmosphere and climate models, the key science knowledge gaps regarding spaceflight emissions are: (1) models that predict EI profiles need improvement to include all important components, altitudes, and propellants; (2) a lack of predictive models to describe emissions from reentering spacecraft; (3) a lack of in situ plume measurements to validate emission models; (4) a lack of remote sensing measurements of reentry plumes to guide development of emission models; (5) a lack of laboratory and test stand data to provide chemical rate constants and rocket exit plane composition; (6) and most importantly, a lack of overall direction and program management to guide increased science and technology research efforts to assess the impact of the spaceflight industry.

C. Science Questions That Need to be Answered

(1) What gas and aerosol compounds are emitted by rocket engines?
- (1a) How do rocket emissions vary by altitude and propellent type?
- (1b) How do models of rocket engine emissions compare to measured emissions?
- (1c) What are emission index and microphysical properties of rocket BC?

(2) How do rocket emissions affect the global atmosphere?
- (2a) How do rocket emissions evolve from near field plume to far field grid box scales?
- (2b) What are the predicted climate and ozone impacts of representative launch scenarios?
- (2c) What are the most important rocket emission components?
- (2d) How do simulations from different models compare?

(3) What gas and aerosol compounds are emitted by reentering satellites and rocket upper stages?
- (3a) What are the metallic vapor and particle populations in near field reentry plumes?
- (3b) How do reentry emissions vary with altitude?
- (3c) How do models of reentry demise compare to reentry observations?

(4) How do reentry emissions affect the global atmosphere?
(4a) What processes transport reentry emissions from the mesosphere to the stratosphere?
(4b) What are the chemical and optical properties of reentry aerosols?
(4c) How do reentry metals affect the properties of sulfate aerosol?
(4d) What are the predicted climate and ozone impacts from reentry emission scenarios?

(5) How do space industry emissions affect the mesosphere and lower thermosphere?
(5a) How are rocket plumes above the homopause different from below?
(5b) How do rocket plumes affect the MLT from regional to global scales?
(5c) Could cumulative launches affect radio propagation or night sky brightness?

(6) How will space industry emissions grow and change in the future?
(6a) What are representative pathways of spaceflight emissions?
(6b) How are reentry emissions coupled with space debris mitigation regulation?
(6c) What are the actual detailed properties of spacecraft and propellants?

D. What is Needed

Research needed to close the knowledge gaps covers seven broad areas:

1. Creation of new predictive models: advanced rocket combustion, reentry vaporization aerosol production, plume to grid-scale evolution and thermosphere and space weather impacts
2. Collection of new plume data to validate the models: in-situ plume composition (10-18 km), launch plume spectral (0-200 km), reentry plume spectral (50-80 km), and thermosphere (space weather).
3. Collection of new laboratory and engine test stand data: heterogeneous reaction rates, aerosol optical properties and rocket engine nozzle exit plane composition.
4. Comparison and validation of models using newly acquired data: rocket combustion and emissions and plume to grid-scale dispersion.
5. Scenario construction using plausible technologies and timelines: coupled launch and reentry of large LEO constellations, technology pathway variations and develop metrics.
6. Global atmospheric and coupled modeling using inputs from plume models and scenarios: assessment of launch impact, assessment of reentry impacts and cooperative assessment of alternate technology pathways.

These activities collectively are sufficient to generate comprehensive and validated input data for the global models. The global models can then reliably be used to provide policymakers with needed information.

E. Relevance to NASA

Historically, NASA has been the agency responsible for assessment of aerospace propulsion on the atmosphere including subsonic and supersonic aviation (NRC, 1999). The models and data collected to support those assessments have served to importantly advance atmospheric science generally and have supported the understanding of climate and ozone generally. Observation and modeling of launch and reentry emissions is a natural extension of these activities. NASA's Earth Science and Space Technology as core competencies and the experience to coordinate work with universities, NOAA, NCAR, and other agencies are key assets which would be very useful in this effort.

Additionally, NASA has the relevant tools and institutions that are needed for assessment of these impacts. For example, measurements of launch plumes could be done at the Kennedy (NASA) and Vandenberg (USSF) launch sites in partnership between the two organizations, as well as university and international partners. NASA has a fleet of aircraft and a variety of instrumentation for them that could be used make the relevant in situ and remote measurements, as has been done in the past.

Climate modeling at the Goddard Institute for Space Studies (GISS) and Goddard Space Flight Center (GSFC) has been used to assess the environmental impacts of many different human activities including supersonic transport, ozone depleting substances, greenhouse gasses, sector specific emissions, aviation, and others for both historical practice and for future scenarios for both air quality and climate. The GISS model has fully interactive atmospheric composition with whole atmosphere chemistry (Shindell et al, 2006), aerosol modules (Bauer et al., 2020), and a well-resolved stratospheric circulation (Rind et al., 2022) with an upper bound of about 80 km. These tools allow for the construction of new spatially and temporally variable emission profiles using all the relevant species.

F. Coordinated and Sustained Effort

Assessment of space industry launch and reentry emissions at a level appropriate for expected emissions growth in coming decades will require a managed and sustained effort, integrated across research agencies. The broad outline of a coordinated and sustained research effort, consistent with existing NASA capabilities, responsibilities, and partnerships is presented here. Such an effort would also have the benefit of encouraging a new, more diverse generation of researchers and building a future Earth Science and space industry workforce.

G. Technical Approach

Assessment of the potential atmospheric impacts of the space industry requires a scientifically sound understanding of the nature and quantity of emissions produced by rocket launches and reentering spacecraft. The physical and chemical processing of newly emitted launch and reentry plumes from the vehicle scales (m), to model grid box scales (10^5 m), and to global scales (10^7 m) must be described. This scientific and engineering capacity, coupled with plausible space industry development pathways, are prepared as inputs by global simulations to predict the cumulative impact of space activities on the atmosphere. The various tools and models that cross spatial and temporal scales from the emitting vehicle to the global atmosphere are checked and improved by measurements of the emissions and the atmosphere's response. This approach is proven scientific and policy process that has improved our understanding the impacts of aviation, supersonic transports, and geoengineering (Lee et al., 2021).

Spaceflight emissions can be studied within this "models guiding measurements and measurements improving models" framework by first decoupling launch emissions and reentry emissions and studying them as separate emissions as they are separated in altitude and composition. (The annual mass fluxes are coupled in the long run by space debris mitigation regulation.) The main impacts of both launch and reentry emissions concerns the net response of the lower and middle atmospheres which determines the (surface) climate forcing and chemical (ozone) changes. Launch emissions also have an upper atmosphere component that is important because as much as 25% of the propellant from an orbital launch is burned above 90 km where the atmosphere transitions to LEO vacuum. Important space weather phenomena that have technology impacts occur in the thermosphere and could affect LEO satellite constellations.

The overall scientific approach includes in situ, remote, and ground test measurements of rocket plumes across an age spectrum (from the nozzle exit plane, to hours old diffusing middle atmosphere plumes, to weeks old thermospheric plumes), remote sensing of reentry plumes, and laboratory measurements of important aerosol microphysics and chemistry. The measurements are used to better understand the unique process and regional phenomena associated with spaceflight emissions and improve and validate emission models so that arbitrary future emissions can be reliably specified as input for global atmosphere simulations This approach was proven in the 1995-2005 time frame when the ozone depleting effects of solid rocket motor (SRM) exhaust was a serious concern. An interagency program of models and measurements successfully demonstrated how to reduce space launch uncertainties (Ross et al., 1999).

The following proposed experiments and model developments are proposed with rationale, indication that the specified platforms, instrumentation, and models are TRL 7 or greater. Some data collects are TRL 9 and could be applied to high value Proof of Concept data collects that would provide immediate, first of a kind, data and lay investment ground work for future research; these are indicated in **bold.**

G.1 Rocket Plume Intercepts: In situ measurement of rocket plume chemistry and dynamics are needed to validate far-field plume models and provide input parameters to global models. The NASA WB-57F aircraft, equipped with a variety of instruments that make up the proven NOAA SABRE instrumentation suite, will be flown through rocket plumes between 5 and 120 minutes after launch. The goal is to obtain measurements of plume composition that can be used to infer rocket engine emission and the relevant processing of the plume as it expands to grid scales. Only one instrument (plume lidar) requires new development.

Measurements: CO_2, H_2O, O_3, NO, NOy, BC, MET, CO, CO_2 are used to (1) plume dilution, (2) important emission indices EI(BC), EI(NOx), EI(VOC), (3) plume chemistry by comparing measurements to plume box models, and (4) evaluate models of rocket engine combustion.

Science questions addressed: (1), (2), and (5)

Operations: Fly 8-10 plume sampling missions during specified periods out of Ellington Field (JSC) to FL or TX launch sites during 2025 and 2026.

Readiness: The NOAA SABRE payload is planning to execute missions in FY25.

Require funding for aircraft ops, instrument operation, and mission coordination.

G.2. Rocket Plume Remote Sensing: Remote sensing measurement of rocket plume chemistry and dynamics are needed to validate emission models and provide input parameters to far-field plume models. multispectral observation of rocket plume to infer rocket engine emissions. The NASA WB-57F or a GV aircraft can carry using flight proven SAMI multispectral imager (LaRC) to obtain data on rocket plume afterburning chemistry and dynamics as a function of altitude for different propellant types.

Measurements: Multispectral narrow bandpass VIS and MWIR high spatial resolution imagery and high spectral resolution VIS/MWIR spectrographs of rocket plumes from 5 - 140 km altitude which includes fully afterburning (0-10 km), middle atmosphere transition (10-60 km), and afterburning shutoff regions (>60 km).

Science Questions Addressed: (1), (2), (5), and (6)

Operations: Fly 8-10 rocket launch target missions from Ellington Field (JSC) to FL or TX launch sites during 2025 and 2026. The missions would include kerosene, LNG, and solid propellant rocket engines.

Readiness: SAMI sensor will reach TRL 8 (for WB-57F and G-V) by middle of FY24 and could be **ready for an early Proof of Concept data collect in early FY 25.**

Require funding for aircraft ops, sensor operation, and mission coordination. **Early Proof of Concept FY 25 mission.**

G.3. Reentry Remote Sensing: Very little is known about how satellites and rocket stages vaporize and recondense particles in mesospheric plumes. Multispectral remote sensing of reentering objects is needed to measure the vertical profile and horizontal extent of reentry destruction and vaporization, particle production, and validate NASA models of spacecraft demise during reentry. The NASA WB-57F or a GV aircraft can carry the flight proven SAMI multispectral imager (LaRC) to obtain data on spacecraft vaporization and aerosol production. The data will be used to improve agency models of spacecraft reentry (including NASA/ODPO) and demise and provide improved input for global atmosphere models.

Measurements: Multispectral narrow bandpass VIS and MWIR high spatial resolution imagery and high spectral resolution VIS/MWIR spectrographs of reentry plumes from atmospheric interface (100 km) though vaporization and break up (85-55 km). Selected bandpass imagery provides vaporization profiles of specific elements and alloys.

Science questions addresses: (3), (4), (5), and (6)

Operations: Fly 4-6 reentry missions during 2025 and 2026 from San Diego NAS CA using information provided by cooperating agencies (DOD, FAA, or FCC) to target specific reentries during 2025 and 2026. The missions would include satellite and upper stage reentries.

Readiness: SAMI sensor will reach TRL 8 (for WB-57F and G-V) by middle of FY24 and could be **ready for an early Proof of Concept data collect in early FY 25.**

Require funding for two years for aircraft ops, sensor operation, mission planning and data analysis. **Early Proof of Concept FY 25 mission.**

G.4 Reentry Emissions Model Development: Understanding the atmospheric impact of vapor and aerosol generated during reentry requires emission scenario input data for global atmosphere simulations. The NASA Space Debris Program Office (JSC) and space regulatory agencies (FAA and FCC) maintain tools to predict reentry heating, break up, and vaporization and analyze risk but do not include emission profiles. These tools could be improved and modified to predict emission profiles of the type required as input to global simulations. The tools would also be used to plan remote sensing data collects (C. above) and interpret the multispectral data from the airborne sensors.

Models: Numerical tools that could serve as the basis for a reentry emissions model include NASA's Object Reentry Survival Analysis Tool (ORSAT) and ESA's Spacecraft Atmospheric Reentry and Aerothermal Breakup (SCARAB) reentry analysis tools. The present output from these tools would be needed to plan reentry remote sensing campaigns and the data from those campaigns would provide a basis for adding elemental emission predictions.

Science questions addressed: (3), (4), and (5)

Readiness: The operational reentry tools are TRL 8 and ready to support remote sensing campaigns and support improvement efforts, possibly may be conducted in late 2024.

Require funding for over two years for model improvement and modification, input parameter specification.

G.5 Middle Atmosphere Global Circulation Models: Emissions from rockets and reentries accumulate in the middle atmosphere (lifetime of about 4 years) and become entrained in the global stratospheric circulation and so produce the main global impacts. Spaceflight emissions present unique challenges to global models such as accounting for transport of reentry emissions from the mesosphere into the stratosphere, including coupled chemistry and radiation, and cloud nucleation. Comparison of the results of simulation of standard emissions using different models is required to understand impacts with high confidence (e.g., Gunnar et al., 2022).

Models: Several different community standard models have been used to analyze rocket emissions including WACCM (Maloney et al., 2022), ModelE (Tsigaridis et al., 2023), and GEOS-Chem (Ryan et al., 2022). These models can be adapted and used in a coordinated way with standardized emission scenarios to understand launch and reentry emissions with a view to the different domains, strengths, and weaknesses of each model.

Science questions addressed: (2), (4), and (6)

Readiness: All of these models are long accepted simulation codes and could be ready to support new investigations immediately (2024).

Require funding for over three years input specifications, simulation time, and analysis.

G.6 Upper Atmosphere Global Circulation Models: Spaceflight emissions into the middle atmosphere largely determine global climate and ozone impacts but are not easily detectable. It is not widely appreciated however that as much as 25% of a rocket's propellant is burned in the thermosphere and spaceflight emissions into the thermosphere are easily detectable from ground and satellite based sensors. Indeed, twilight launch plumes, bright reentry plumes, and post-launch regional airglows are widely seen by the public. These visual displays may at some level of spaceflight activity affect ground based astronomy, much as the satellites they launch are known to do (Hasan, 2023). Thermospheric impacts including airglow, ionospheric holes, and high-altitude cloudiness, generally "space weather", are an increasingly active area of research and spaceflight will play an increasing role as part of that background.

Models: Several different community standard models have been developed to model the upper atmosphere and space weather including WACCM-X and TIME-GCM though they have not been used to model thermospheric space emissions. These models can be adapted and used in a coordinated way with standardized emission scenarios to understand how launch emissions affect the upper atmosphere space weather.

Science questions addressed: (2), (4), and (6)

Require funding for over three years for model input development, input specifications, simulation time, and analysis.

G.7 Upper Atmosphere Plume Remote Sensing: Thermospheric impacts including airglow, ionospheric holes, and high-altitude cloudiness, generally "space weather", are an increasingly active area of research and spaceflight will play an increasing role as part of that background. These perturbations are large enough that they can been seen by the naked eye in the days following launch (Stevens et al., 2012). These molecular emissions and high-altitude cloud formations and ionospheric "holes" (Chenegor, 2022) present important signatures of the impact of rocket emissions in the thermosphere. These visible and wide area coverage emissions could as some level of space activity become an interference for ground-based astronomy.

Measurements: Multispectral narrow bandpass imagery of visible scattered, OH, and NO emission high spatial resolution imagery and high spectral resolution VIS/MWIR spectrographs of reentry plumes from atmospheric interface (100 km) though vaporization and break up (85-55 km). Selected bandpass imagery provides vaporization profiles of specific elements and alloys.

Science questions addresses: (1), (2), and (5)

Operations: Deploy ground based remote sensors at locations where upper atmosphere rocket plume impacts on nightglow and upper atmosphere cloudiness

Readiness: Sensors to observe space weather are available at TRL 7.

Require funding for two years for sensor development, planning and coordination, and sensor deployments.

G.8 Laboratory Studies of Critical Processes: Many physical, chemical, and hardware focused process that are critical to understanding of the impacts of launch and reentry emissions can only be understood by laboratory measurements. These include investigations of natural and spaceflight aerosols and measurement of rocket engine emissions in order to provide actual inputs to plume chemistry models.

Measurements: Highest priority include changes in sulfate aerosol properties caused by metallic inclusions from reentry emissions, measurement of rocket engine exit plane exhaust composition at test stands, and chemical rate constants for specific reactions.

Science question addressed: (1) – (5)

Readiness: Requires investment in laboratory hardware (agency and university) and cooperative planning at national engine test facilities.

Require funding for two years.

G.9 Representative Emissions Pathways Development: The space industry's rapid growth and development and the demands for data and input demands from the modeling and measurement planning activities requires the development of standard ways of specifying space industry emissions. This is similar to the IPCC specification of GHG emissions to enable model intercomparison and exploration of policy options. The same needs to be done for spaceflight by different propellant, reentry, launch vehicle, constellation size, space debris mitigation, GEO and MEO systems, and lunar and planetary options.

Readiness: The fundamental space technology and atmospheric science methodology has been in development for several years and is ready for **Proof of Concept** fast track development for use by the modeling, measurement, and policy communities.

Science question addressed: (6)

Require funding for two years.

Early Proof of Concept scenarios in early FY25.

H. Workshop (Spring 2025): **The Impacts of a Growing Space Industry on Earth's Atmosphere- Research Challenges and Opportunities:** As it is evident from section C "Science Questions", this phenomenon is complex, and we need to engage and consult a broader community of experts, thinkers, planners, researchers and technologists. With this goal we are planning to hold a workshop "The Impacts of a Growing Space Industry on Earth's Atmosphere- Research Challenges and Opportunities," sometime in Spring 2025.

It is a joint effort by NOAA, NASA and NSF.

Workshop Participants:

Researchers at academic and government organizations

Representatives from regulatory agencies (FCC, FAA, DOC)

Representatives from commercial space

Other key stakeholders (DoD, ESA, OSTP, IAU)

Workshop Outcomes:

F. Increased awareness of the wide range of spaceflight impacts among participants.
G. Review of the scientific state of the art and identification of important knowledge gaps
H. Review the information needs of regulatory and science agencies.
I. Recommendations for research directions to close knowledge gaps
J. Final Report

I. Partners and Stakeholders

A number of government agencies have an interest in spaceflight sustainability. The FCC and FAA have regulatory control over launch and orbital operations, respectively. The FCC recently established a Space Bureau that will examine (among other things) environmental impacts, though the GAO (GAO, 2022) reports that FCC does not currently have sufficient technical capabilities and will need to rely on other agencies such as NASA for global modeling of spaceflight emissions.

NOAA, which is given budget authority for spaceflight impacts through Earth Radiation Budget research, is an historical NASA partner in Earth System research. USSF is dependent on commercial spaceflight which is subject to federal environmental regulation and so it has a compelling interest in partnering in research related to sustainability (Ross and Toohey, 2018, Ross and Jones, 2022).

Two division of NSF, namely Atmospheric Chemistry and Aeronomy have shown interest in contributing funds to our effort (negotiation are underway). NSF also has very productive relationship with Space-X and they are willing help us in getting some support from them.

Various complementary simulation tools from other US agencies, such as the GEOS model (NASA GSFC), are able to perform studies of the impact of spaceflight emissions. NOAA (GFDL) has a climate model that handles aerosols in the stratosphere (some funding through ERB is going to that) are also available. NCAR (NSF) has a model that can do this work (CESM) and has recently been incorporating a sectional aerosol model for public release, also partially funded by the NOAA ERB program.

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