Whitepaper

Understanding the Atmospheric Effects from Spacecraft Re-entry

A summary and key facts

The aim of the workshop held on the 10th -11th of January 2024 in ESTEC was to bring together atmospheric chemists and physicists, material experts, the space industry, and international space research related organizations to highlight the gaps in our understanding of the modelling and how we can improve testing to obtain relevant data and suggest appropriate mitigation and regulatory measures.

Introduction

The expected number of launches and spacecraft re-entries into the Earth's atmosphere raise concerns for the future, these include mega-constellations and a significant number of re-entry vehicles that are in development. The consequences of space activities and the direct and indirect impacts to the mesosphere, stratosphere and troposphere are still unclear and must be understood. Anthropogenic injection was highlighted as already significant compared to the natural meteoric sources. NOAA sampled stratospheric particles and found that, 10% of them contained spacecraft metals. Expertise on meteoroids' re-entry observations and characterization could be key to understanding the ablation profiles and enhance the multi-disciplinarity of the topic. ESA seeks to build consensus around actions to have a holistic view and facilitate efforts to develop collaborative and harmonized upper atmospheric research. The paper is structured in three sections: the state of the art identified during the workshop, a list of actions proposed by the participants, and on-going projects and opportunities. Each section is therefore organised for clarity in 3 main disciplines: emissions profiles, atmospheric chemistry, atmospheric modelling and impact assessment.

State of the art

Emissions profiles:

- Natural influx to enter in Earth's atmosphere is about 12'400 tons/year (error of factor 2). The estimated amount of anthropogenic input was around 890 tons/year in 2019.
- Metals such as aluminum, lithium and copper from spacecraft ablation reach higher concentrations than their natural inputs.
- Meteors enter faster than spacecrafts, thus they tend to ablate at higher temperatures and altitudes.

- Spacecraft ablation happens between approx. 100 km to 40 km. However, emissions profiles depend on many variables including the material composition of the spacecraft and mission characteristics.
- Rocket bodies release more mass than satellites, due to intrinsic higher masses in the structures.
- Rocket launch soot emissions at stratospheric conditions are not characterized.

Atmospheric chemistry:

- NASA WB-57 aircraft - 2023 SABRE flights from Alaska at up to 19 km altitude sampled 500,000 particles. About 20% of particles in air descended from the mesosphere contained metals specific from spacecraft equipment, leading to an estimate that 10% of particles in the stratosphere contain metals from spacecraft ablation.
- Metallic particles in the lower stratosphere tend to have coagulated and have a thick coating or are dissolved in sulfuric acid.
- Particles contribute to mesospheric (PMC[1]) and stratospheric (PSC[2]) cloud nucleation.
- PSC form at higher temperatures (and or/lower supersaturation with respect to ice) than expected because the freezing points of the droplets are raised following the inclusion of metallic particles.
- There could be major changes in polar stratospheric clouds if even a tiny fraction of the spacecraft particles efficiently nucleate ice or nitric acid trihydrate (NAT). The impact on ozone depletion needs to be understood.
- It is not clear if copper or another metal in sulfuric acid could catalyse heterogeneous chemistry in the ozone layer.
- Soot formation quantities arising from ablation are uncertain.
- How much is it affecting the ionospheric electric conductivity and electric field.

Atmospheric modelling and impact assessment:

- Every 6 months particles in mesosphere are flushed down towards the winter polar stratosphere. The middle atmospheric circulation continuously transports ablated material (whether from meteors of satellites) towards the winter pole and into the winter polar vortex.
- Chemistry, climate, and radiative models have already been coupled in several study activities.
- Particles larger than 1 micron will sediment rapidly through the mesosphere and stratosphere. Therefore, only a fraction of the ablated particles may have stratospheric effects.
- The impact of metal particles and aerosols have not been assessed for climate and ozone depletion.
- Effects of PMCs and PSCs on climates are unclear.
- In 1964 a failed navigational satellite released plutonium in the upper stratosphere; its subsequent worldwide deposition presented an opportunity for testing global models to track debris transportation.

Measurement capabilities:

- Weather balloons, high altitude research aircraft, satellites, sounding rockets.
- Techniques exists to observe meteors based on plasma, lidar or spectroscopy.

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[1] Polar Mesospheric Cloud
[2] Polar Stratospheric Cloud

- Ground facilities: Instituto de Astrofísica de Andalucía- MASI facility, Stuttgart Uni - Plasma Wind Tunnel, DLR – High-Enthalpy Wind Tunnels, ESTHER - European Shock-Tube for High Enthalpy Research, PALS – Prague Asterix Laser System, Karlsruhe Institute of Technology- AIDA Simulation Chamber facilities.

Proposed Actions
Emissions profiles:

- Improve all ablation models.
- Improve material datasets for spacecraft.
- Improve particle emission modelling.

Atmospheric chemistry:

- Improve the understanding of stratospheric/mesospheric nucleation mechanisms, and correlation to particles released.
- Laboratory experiments to study heterogenous chemistry of acidic gases (e.g. HCl) on relevant particles (e.g. alumina) under stratospheric conditions, and the ice nucleating abilities of these particles.
- Studying reaction kinetics and photochemistry under with relevant atmospheric conditions in different parts of the middle atmosphere.
- Understand the origins of stratospheric sulfuric acid particles with and without meteoric metals.
- Understand the ice nucleation activity of meteoritic and spacecraft ablation particles as they impact PMCs and PSCs.

Atmospheric modelling and impact assessment:

- Study the correlation between mesospheric particles and stratospheric particle morphology distribution.
- Use a specific material existing in projects to be released in the upper atmosphere as a tracker for improved modelling.
- Improve understanding on particle size, mass distribution and optical properties of Al_2O_3 and BC aerosol from object re-entry for modelling.
- To understand the emission indices of byproducts from liquid methane fuel.
- Model and measure the impact of PSC and PMC on radiative balance and ozone depletion.
- Understand if PMCs, could have an impact on future technologies such as airbreathing propulsion systems.
- Measure and monitor the evolution of metals and small aerosols (<< 1 micron) and compare with ablation models.
- Model the ablation process and the coagulation and transport of the ablated material, to determine the size distribution and where the material is deposited and transported to.

Setting-up community/centre of excellence:

- Need has been identified to establish a scientific community based around developing a better understanding of this topic.

On-going projects and opportunities

- ESA Cluster II re-entry campaign: On-ground observation.
- ESA DRACO demise demonstrator: calls are open for optional scientific payload.
- ESA FIREWALL will sample and analyse the emissions from reusable demonstrators (such as THEMIS's plume).
- PALMS instrument is proposed to do a measurement campaign in 2025 for tropical areas, where there is less contamination.
- CAIRT (candidate to EE11[3]) could be used for a tracer experiment for alumina particles using an infrared imager.
- AMOS – global detection capabilities
- DLR -TEMIS-Debris and sounding rocket-based flight experiments for atmospheric studies.
- MASI instrument is being modified to build an atmospheric chemistry simulator.
- Use stratospheric balloons to reach higher sampling altitudes (up to 35 km) and perform electron microscopy on samples.
- Instrumentation on rocket re-entry stages.
- ESA Earthcare can help with overview of aerosol and cloud impact.

Launch and Re-entry Databases:

- Home | Grav (esa.int) - Simulations can be performed to estimate the risk of re-entries.
- https://discosweb.esoc.esa.int/ - DISCOS (Database and Information System Characterising Objects in Space)
- https://sdup.esoc.esa.int/ - DRAMA (Debris Risk Assessment and Mitigation Analysis)
- https://www.planet4589.org/space/gcat/index.html - General Catalog of Artificial Space Objects

Prepared in collaboration with the participants of the workshop: Understanding the Atmospheric Effects of Spacecraft Re-entry (10-January 11, 2024): Overview · Indico at ESA / ESTEC

[3] ESA Earth Explorer 11