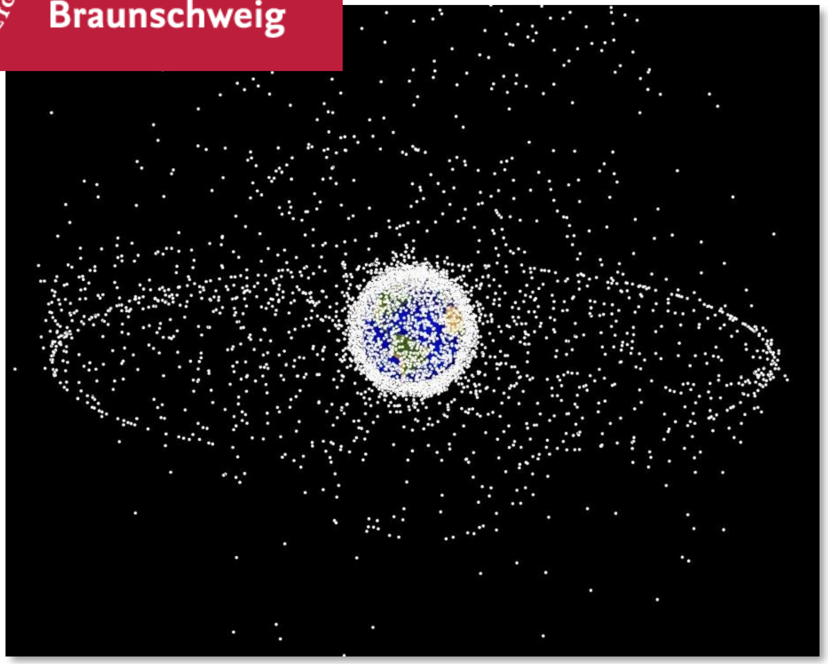

Concerning the Impact of Deorbiting Spacecraft to the Upper Atmosphere

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Images: Left: Earth space environment (NASA ODPO); Top right: ATV-1 reentry (NASA/ESA); Bottom right: Chelyabinks meteor trail (Nikita Plekhanov)

Motivation/Problem

- Advancing commercialization of space industry
- Upcoming large satellite constellations (LC)
- Mitigation guidelines due to increasing space debris numbers

→ More and more human-made objects (satellites, rocket bodies, etc.) will reenter the atmosphere and disintegrate adding material to the upper atmosphere

Arising questions:

- How much mass enters annually?
- How much of this mass is injected into the atmosphere in what state?
- Which chemical composition does this material have?
- How will this change in the future (especially regarding LC)?
- How does this compare to the natural injection of meteoroids coming from asteroids, comets, etc.?
- Finally: How does this influence the environment/upper atmosphere? → Importance of metal injection

Annual Mass Input

Natural

- Differentiation between interplanetary dust particles (IDPs) and larger impactors ($>10^{-2}$ g)
- IDP mass input: Many different studies with very different values:
  - Model of solar meteoroid flux *(Grün et al., 1985; Divine, 1993; Staubach et al., 1997; Dikarev et al., 2004)*
  - Visual, (radar), and satellite data *(Hughes, 1978)*
  - Impacts on satellite *(Love and Brownlee, 1993)*
  - Many other studies (see *Plane, 2012;* others)

  → About 20 kt/yr most probable
- Larger impactor mass: about 2 kt/yr (after *Brown et al., 2002)*

→ **Around 22 kt impact Earth every year**

Anthropogenic

- Today about 190 t/yr, 60% satellites, 40% upper stages (combination of *Liou et al., 2018*; *McNair and Boykin, 1966*)
- But: Core stages do reenter right after liftoff of a launch vehicle → Extra 0.5 kt per year
- With future LC: 2 Scenarios:
  1. Most probable scenario: 14000 additional satellites and 235 upper stages within 5 years

     → 1 kt/yr (additional)
  2. Maximum scenario: 25000 additional satellites, 380 upper stages within 5 years

     → 1.7 kt/yr (additional)

→ **2.4 kt/yr at maximum possible in the future**

Composition

Natural

- IDP composition after *Schramm et al., 1989; Arndt et al. 1996*
    - Largely silicates, but have a considerable amount of organic elements (51%) as they originate mostly from comets *(Jenniskens, 2015; Zolensky et al., 2006; Bardyn et al., 2017)*
- Large impactor composition is modelled after the meteorite composition found on Earth *(Grady, 2000; Lodders and Fegley, 1998; Mittelfehldt et al., 1998; Wasson, 1974; Demidova et al., 2007)*
    - Originate mostly from asteroids *(DeMeo and Binzel, 2008; Fernández et al., 2005; Bottke et al., 2002)*
    - Composition is less organic

→ 35 % of the mass are metal elements. Most abundant elements are O, Fe, Si, Mg, C, S each contributing more than 1kt/yr to the influx

Anthropogenic

- Hard to estimate as every object is different, but classes (e.g. rocket bodies) have similar composition
- Very high metal abundance (up to 95 % for upper stages), especially Al, Fe, and Ni coming from various alloys used for structural parts *(Henson, 2018)*
- Satellites have lower metal abundances, although they are still higher than for the natural material
- For satellites more diverse materials are used *(Finckenor, 2018)*

→ High metal abundance, non-metallic elements only minor. Main elements are Al, Fe, Ni

Atmospheric Processing upon Reentry

Highest uncertainties

Not all the mass is injected into the atmosphere, a portion hits the ground!

Different ablation products: Atoms, Dust (aerosols), Ground-reaching material (meteorites, debris)

Natural	Anthropogenic
▪ IDPs: • Atoms lost through sputtering *(Rogers et al., 2005)* at high altitudes and ablation *(e.g. Rietmeijer, 2002)* at lower altitudes • After that are slowed down → unmelted aerosols • All the mass is injected into the atmosphere! ▪ Larger impactors *(Baldwin and Sheaffer, 1971; Klekociuk et al., 2005; Borovicka et al., 2019,* others*)*: • Negligible sputtering • Atoms and dust lost through ablation → Dust recondenses • Increasing aerosol mass with impactor size • Around 15 % of the mass reaches the ground	▪ Different ablation behavior due to slower speeds, lower entry angle ▪ Higher mass portion should survive, but measures to reduce risks on the ground are taken→ complete demise is the goal → intentional breaking points, etc. ▪ Our preliminary estimate: 30% gets to the ground, the rest is equally ablated in atomic and aerosol form

Summarizing Results

- Today, the natural atmosphere injection dominates, human-made objects contribute less than 1% of the mass
- With future LC this changes:

1. Probable Scenario: 4% of the annually injected mass is human-made. Relative injection of metals is even higher (9%)
2. Maximum Scenario: 7% of the annually injected mass is human-made. Relative metal injection up to 16%

- The anthropogenic injection of some metal elements might even prevail the natural injection: For example Al: 0.27 kt/yr natural, 0.37 or 0.62 kt/yr (Scenario 1 and 2 respectively).
- Disproportional increase of the injection of aerosols from human-made objects

→ With future satellite constellations, the anthropogenic injection becomes significant!

Problems and Outlook

- Although vast amounts of literature are available for some topics, often quite different values or results are given (e.g. natural mass input)

→ Extensive study has to be performed (Paper is in preparation)

→ Here given values might change marginally, but the overall significance of the anthropogenic injection remains

Possible effects on the environment?

- Climate (aerosols have a radiative forcing effect, see *Lawrence et al., 2018*)
- Ionosphere (increase of the injection of atoms and ions)
- Chemical processes in the atmosphere (maybe ozone?)

→ Problems should be addressed in the future!

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