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Troubled Orbits and Earthly Concerns: Space Debris as a Boundary Infrastructure

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Abstract

Like other forms of debris in terrestrial and marine environments, space debris prompts questions about how we can live with the material remains of technological endeavors past and yet to come. Although techno-societies fundamentally rely on space infrastructures, they so far have failed to address the infrastructural challenge of debris. Only very recently has the awareness of space debris as a severe risk to both space and Earth infrastructures increased within the space community. One reason for this is the renewed momentum of interplanetary space exploration, including the colonization of the Moon and Mars, which is part of transhumanist and commercially driven dreams of the so-called New Space age. Understanding space infrastructures as inherently linked to earthly infrastructure, we attend to the ways in which space debris, a once accepted by-product of scientific-technological progress, economic interests, and geopolitics,

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increasingly becomes a matter of concern. Drawing on qualitative interviews with European space sector representatives and work in Science and Technology Studies on infrastructures, we argue that their discursive efforts and visual representation strategies coproduce space debris as a boundary infrastructure. We suggest considering this boundary infrastructure as relating orbital environments and the planet through enacting sustainability and responsibility for beyond-planetary environments.

Keywords
space debris, sustainability, social studies of outer space, boundary infrastructure, co-production

Introduction

Over the last decade, space debris has become a growing concern in the global space community. Space debris—defunct rockets stages, old satellites, objects released during space missions, and thousands of small fragments generated by their collision[1]—became well-known beyond the space sector with the Hollywood drama *Gravity*. In this movie, two astronauts struggle for survival as pieces of space debris damagingly hit their spaceship. In real life, space debris incidences are not less spectacular: The accidental collision of two communication satellites, Cosmos 2251 and Iridium 33 in 2009, created over 140,000 pieces of space debris and contributed significantly to the total number of debris fragments accounted for today. Due to the high speed with which space debris circulates in Earth's orbit, even tiny pieces can cause severe damage when impacting operational spacecraft like satellites or the International Space Station. In 2018, news outlets worldwide covered the story of Tiangong-1: The Chinese-operated space station became dysfunctional and uncontrollably reentered Earth's atmosphere, potentially threatening both space infrastructures and lives on Earth.

With the commercially driven "New Space age," space debris is increasingly framed by space policy makers as a sustainability risk: private space entrepreneurs, spearheaded by Silicon Valley tech-capital, begin adding to the large pile of twentieth-century space debris by launching unprecedented numbers of new satellites into orbit. Although the notion of a vast universe is persistent, orbits, the "roads" on which satellites circulate the Earth, are far from endless. As contemporary societies largely depend on functioning

satellite networks for data transfer, communication and navigation services, and climate and crisis monitoring, space debris is understood as a threat to planetary and orbital infrastructures. For some, the congested orbits might even put an end to transhumanist ideas of escaping our planet for other places in the cosmos, as safe launches of future spacecraft would be hindered by space debris. This new risk awareness is particularly strong in Europe, with the European Space Agency (ESA) aiming to take the lead in space debris removal efforts (ESA 2013) and European Union institutions repeatedly calling for action to reduce potential space debris emissions already in the construction phase of space infrastructures (European Parliament and Council 2014).

In this paper, we argue that space debris is anything but a distant outer space phenomenon and has become a concern transgressing the boundaries between the planet and its orbits in outer space. As such, it closely links to questions of responsibility and sustainability, which are adopted by space sector experts to make plausible what we propose calling inherently inseparable *orbital-planetary* environments.

We explore this notion by tracing how European space professionals construct space debris as an issue that links notions of orbital and planetary sustainability. We observe that in doing so, they dissolve traditional (discursive) boundaries between orbital and planetary responsibility and instead relate to an orbital-planetary risk environment constituted by the presence of space debris. In our analysis that builds on seventeen expert interviews, we specifically focus on the strategies of European space sector professionals in linking space debris to broader environmental concerns, thereby framing it as a rising sustainability risk. More specifically, we attend to the specific sites of discursive and representational practices by which the encompassing orbital-planetary nature of space debris sustainability is coproduced. Our approach draws on the concept of boundary infrastructures understood as "objects that cross larger levels of scale than boundary objects" (Bowker and Star 1999, 287) to account for how interviewees describe space debris as constituting a "shared space" (Star 2010, 602-603) that encompasses Earth and its orbital "backyard" in outer space. It also conceptually refers to sites of co-production (Jasanoff 2004) to account for field actors' political and ontological troubles in constructing this notion of an inherently interrelated orbital-planetary environment by referring to space debris.

Structuring the paper, we first provide an overview of the literature in Science and Technology Studies (STS) and the emerging interdisciplinary field of "social studies of outer space" (SSOS) on the cultures,

(techno)politics, and environments of outer space. Second, we introduce our conceptual approach to understanding space debris as a coproduced orbital-planetary infrastructure. The empirical part is structured along the lines of discursive storyline and representational strategies employed by European space professionals and the ways they attempt to link orbital and planetary sustainability. Lastly, the discussion and conclusion contextualize our findings considering current STS debates on infrastructures and sustainability. We propose that a better understanding of how we want to live with over 30,000 known debris objects orbiting above our planet is crucial for working toward and caring for sustainable (beyond-)planetary futures—assuming that the way in which space debris is perceived will have strong implications for conceptions of Earth as a socio-ecological moral entity among the space sector in the future.

The Making of Interplanetary Spaces: Co-production and Boundary Infrastructures

This paper contributes to a growing body of work at the intersections of STS, anthropology, and sociology that investigates how outer space is linked to terrestrial concerns and how extraterrestrial materialities and imaginaries impact life on Earth (and vice versa). As spaceflight activities increasingly aim to (re)establish a new "frontier" for exploration and exploitation in outer space (Olson 2012), scholars have recently attended to how interplanetary and Earthly spaces are intrinsically linked (Olson and Messeri 2015)—ontologically, politically, economically, and ecologically. Research in this field has shown how satellite technologies shape security and environmental politics (Rothe and Shim 2018; Witjes and Olbrich 2017; Parks 2005; Redfield 1996), explored how planetary sciences contribute to new place-making practices, and explained how exoplanets become places to be known and explored (Messeri 2016; Valentine 2012).

Specifically, work in SSOS has contributed much to our understanding of how the material politics of single artifacts (e.g., spacecraft) emerge as "global boundary objects" (Rand 2016, 72), transgressing the spatial boundaries that constitute many planetary ontologies (Olson 2013). Conceptual approaches like that of the technosphere (Haff 2014) describe a large-scale sociotechnical system shaped but not entirely managed by human action. These considerations have questioned merely anthropocentric perspectives and dominant preoccupations with planetary problems (Olson and Messeri 2015; Gorman 2014). As Gärdebo, Marzecova, and Knowles (2017, 47) have shown, such anthropocentrism prevents us from recognizing that "the

continual use of satellite technology [. . .] generates new layers of spatial conceptualizations, technological infrastructures, and legislative strategies concerning the management of both, orbital space and the Earth's surface."

Although this emerging body of work provides a valuable point of departure for exploring outer space as co-constitutive of scientific-technological, political, and cultural activities, space debris and the issue of crowded orbits have not been sufficiently empirically addressed. Valuable exceptions are the work of Damjanov (2017), who analyzes space debris as media technology and stresses that "space waste is imbricated in the management of the future as a material force [. . .]" (p. 180), and Gärdebo, Marzecova, and Knowles (2017) who argue that the space debris layer in orbit challenges the notion of the technosphere. Existing STS work on waste, recycling, sustainability, and caring for infrastructures, in contrast, primarily addresses planetary concerns. For instance, Bedsworth, Lowenthal, and Kastenberg (2004) convincingly dissect risk narratives on infrastructural remains like nuclear waste as embedded in policy controversies. Similarly, Gabrys (2009, 2011) explores the unruly agency of waste, challenging concepts of sustainability within demarcated systemic boundaries. However, as orbital and planetary environments are inherently related and co-constitutive of each other, what has been missing so far is analytical attention to the question of how orbital sustainability becomes a matter of concern.

Thus, our article adds to recent work in both STS and SSOS by empirically analyzing how, in the discourses among European space professionals, space debris becomes a narrative ground of arguing for an orbital-planetary relatedness. We do so by building on two specific strands of conceptual work in STS: the idiom of co-production (Jasanoff 2004; Felt 2015; Hilgartner, Miller, and Hagendijk 2015; Pfotenhauer and Jasanoff 2017) and infrastructure studies—in particular, the notion of boundary infrastructures (Bowker and Star 1999; Edwards et al. 2009; Dagiral and Peerbaye 2016).

The idiom of co-production builds on a long tradition in STS that has examined science and technology as social practices that shape, and are shaped by, social and political order. Co-production, as Jasanoff (2004) has outlined, is "shorthand for the proposition that the ways in which we know and represent the world (both nature and society) are inseparable from how we choose to live in it. Knowledge and its material embodiments are at once products of social work and constitutive of forms of social life" (p. 2). Such a perspective on the mutual shaping of science, technology, and social order helps to understand how contextualizing orbital environments and their

planetary counterparts as mutually constitutive renders visible the interdependencies of world-knowing and world-making (Gärdebo, Marzecova, and Knowles 2017).

Jasanoff (2004) identifies four sites of coproductive relationships: the making of collective identities, public discourses, representations, and the governing of institutions (p. 6). For this article, *discourses* and *representations* are particularly relevant sites to trace co-production of orbital and planetary domains in the storyline among European space professionals of how they know about and relate to space debris as a sustainability concern. Following Hajer (1995, 2009), we understand storyline as simplified and condensed articulations of a certain *discourse's* key elements. In our case, this relates to the political regulation of outer space, the technological and economic limits and potentials of spaceflight technologies, and the challenges and opportunities in communicating the societal value of spaceflight to a broader public. With regard to *representations*, we explore how practices of visualizing space debris are negotiated and validated among European space sector professionals. We specifically focus on their sense-making practices in referring to space debris visualizations and how these engage in the construction of an interrelated orbital-planetary environment.

While such co-productionist lenses attune us to the discourses and representations of space debris, they are less sensitive to its material characteristics as an orbital waste formation. Therefore, we draw on the concept of boundary infrastructures (Bowker and Star 1999), which enables us to explore the role of infrastructures in an outer space environment where space debris is moderating the inherent interrelation of orbital and planetary realms. Boundary structures "deal in regimes and networks of boundary objects (and not of unitary, well-defined objects)" (Bowker and Star 1999, 313) and thus allow us to explore how space debris is coproduced as a distributed, yet global infrastructural phenomenon that is more than the sum of individual debris objects: it threatens intact global satellite networks and thereby creates a relationship of infrastructural risk that spans both planetary usage of space-related services and the orbital technologies providing them.

As we show in the fifth section, space debris is often considered invisible and rendered visible only through standardized ways of visual representation. This characteristic corresponds with the notion of infrastructural systems that are "often intended to be so standardized and reliable that they fade into the background, [while] in other circumstances, they are made very visible, by accident or by design" (Henke and Sims 2020, 19-20).

Space debris, as a global phenomenon, can thus be understood as a boundary infrastructure that calls for infrastructural maintenance work by current and future space actors. Debris removal efforts are neither limited to national borders nor single debris fragments belonging to any particular state (ESA 2019).

Acknowledging these aspects, we propose that linking a co-productionist perspective to the concept of boundary infrastructures is helpful to understand how space professionals discursively frame space debris as an orbital-planetary challenge and how they visually represent the corresponding environment as inhabited by debris as a material infrastructure.

Material and Methods

Our material consists of seventeen semi-structured interviews with European space sector professionals conducted between 2017 and 2020. The sample includes a broad range of actors from industry, space entrepreneurs, policy advisors, and public administration officials with technical, legal, or policy expertise that have prominently contributed to storyline of space debris within their respective fields.[2] As our focus is on the prevalent storyline *shared* across the sector, we deliberately refrained from analyzing the interviews according to the interviewees' affiliations with specific communities of practice or institutional regimes within the European space sector. All interviews were recorded, transcribed, and analyzed using transcription and content analysis software.

We used Hajer's (2009) approach to discourse analysis that considers discourse "an ensemble of notions, ideas, concepts, and categorizations through which meaning is ascribed to social and physical phenomena, and that is produced in and reproduces, in turn, an identifiable set of practices" (p. 60). Hajer conceptualizes storyline as condensed articulations of key discourse elements. This approach helps us identify how diverse actors within the space sector discursively refer to questions of space sustainability and the need for responsibility and care for orbital-planetary environments. As storyline are "summarizing complex narratives, used by people as 'shorthand' in discussions" (Hajer 2009, 61), such a focus also allows us to handle the often buzzword-heavy narratives prevalent in sustainability discourse (Müller and Witjes 2014).

To analyze the visual representation of space debris encountered in the discursive practices of interviewees, we draw on work in STS and related fields to discuss the nexus of visuality and materiality. In particular, we focus on how and which things are made visible and investigate the

ontological and political implications attached (Rose and Tolia-Kelly 2016). As Witjes and Olbrich (2017) have argued, visualization technologies do not only enhance human vision but also (re)constitute depicted objects, issues, and processes by making them visible through their socio-technological arrangements (see also: Ruivenkamp and Rip 2014; Haraway 1988; Latour 1986). Studying how researchers of the National Aeronautics and Space Administration's (NASA) Mars Exploration Rover Mission used images to investigate the Red Planet, Vertesi (2014) has shown how visual representations are themselves theory-laden and purposeful practices. We adopt this approach to investigate what challenges interviewees encounter in discussing artificial imagery of space debris originally produced for monitoring, observing, and publicly representing space debris.

Relating Orbital-planetary Sustainability Issues

In the following section, we attend to those discursive practices by which our interviewees raise space debris as a concern. We outline how the storyline they use for this purpose can be seen as enacting an orbital-planetary environment through the notion of responsibility for space debris.

Space Debris as a Concern

Throughout our interviews, interlocutors drew attention to space debris as a tangible, material risk in different ways. However, space debris has not always been a concern for the space community. During the so-called Old Space age, beginning in the 1950s, geopolitical concerns about competitiveness and leadership in space exploration sidelined efforts toward a more sustainable technological usage of outer space; the development of self-disposing satellites or the reusability of rockets was not prominent idea at that time. Only recently has space debris become a concern within the space community and in public perception. This was reflected in many interviews. For instance, interviewees pointed to the need to take urgent action given the negative impacts of continued unsustainable use of Earth's orbits, as the following quote of a space policy advisor and activist shows:

> I think one of the main challenges arising is how . . . stemming from the fact that our society is so dependent, at least our Western society, has become so dependent on space technologies, how we can sustain that and how we can protect ourselves from when things go wrong. (PA 1)

In a similar vein, public administration official (PAO) 1, a space agency engineer, lamented a lack of awareness about the sustainability risk emanating from space debris and the potentially catastrophic consequences that space debris collisions would have for technologized societies.

> If we at some point would say that all our systems would collapse when [space] infrastructure stops working the way we expect it to—if they are not resilient enough, for example. And then, if something happens in outer space—be it the Kessler syndrome or, for example, space weather like a coronal mass ejection that paralyzes our satellite infrastructure, which might very well happen. Would we, as a society, be able to absorb the shock, to compensate for this whole thing or not. (PAO 1)

Portrayals of looming infrastructural collapse, such as this one, were often accompanied by storyline about the impact of space debris on the sustainable future use of outer space. As one of our interviewees put his worries, "[t]he threat is, simply put, that the more debris revolves around in outer space, the more difficult it becomes to conduct spaceflight activities under safe conditions. And if this is not guaranteed, then systems like a satnav become more prone to blackouts in the long run" (PAO 2). He emphasized that rocket launches can only continue if their flight paths in orbit remain safe and unobstructed. In a similar vein, some interview partners voiced concerns about the obstacles that space debris poses to futures space activities, often by drawing on transhumanist narratives of human colonization of outer space (Dunnett et al. 2019).

Such transhumanist visions saw a recent revival and are prominently embraced by New Space entrepreneurs such as Elon Musk. They assume that the ongoing destruction of our home planet through human activity—from devastating natural resources to war and climate disaster—requires a "planetary backup plan" beyond Earth; a last resort on another planet that allows humanity to avoid the need for maintaining planetary sustainability on Earth at all costs. As industry (IN) 1, an engineer at a big European space industry company stated, this would require "transfer[ing] some part of humanity to Mars" (IN 1) or to "one day fly to Mars in case Earth is no longer habitable" (IN 1). In this storyline, polluted orbits would make an exodus to Mars ultimately impossible: if the challenge of space debris in orbit is not tackled, future spacecraft might not be able to launch safely and leave Earth.

Here, we can see how concerns for the sustainability of orbital spaces are intertwined with imaginations of human expansionism beyond the planet. In

some interviews, this perspective was complemented by concerns about how orbital pollution by space debris would eventually hinder critical infrastructures like communication or Earth observation capabilities to function. The following quote by an engineer and start-up entrepreneur shows the growing concern about our dependence on outer space sustainability:

> [O]ne would need to take quite different [more rigorous] actions by now and implement them after decades of controversy on the international level. This is, as sooner or later, orbits in some altitudes are already under threat of becoming unusable. That will happen. And only if something happens at some point, something really severe [. . .] the European Space Agency loses a 300-million-dollar asset [satellite] . . . or the Americans. Then maybe something will change. (SE 1)

By relating planetary to orbital concerns, another interviewee highlighted the need "to take steps toward sustainable development and maybe backup solutions" (PAO 1). This necessity, as PA 1, the space policy advisor and activist, stresses, stems from "the dependence that we have grown on space technology as a society as a civil society [. . .] and how we can mitigate any man-made or natural threats to that" (PA 1).

These concerns are in line with recent literature that sees the accessibility of low altitude orbits as critical to national sovereignty in military reconnaissance, civilian Earth observation, and essential mobile telecommunications systems (Al-Rodhan 2012). While, by international treaty, Earth's orbits are global commons and belong to all humankind in the sense of vertical public space (Parks 2013), the question of how this space is organized and shared remains contested. Space debris and its increasing presence due to New Space endeavors seems to bring a novel sense of urgency to these debates.

Despite this urgency to act as put forward in many interviews, we also identified more attenuating narratives regarding orbital-planetary sustainability. Often, interviewees simultaneously engaged in both: providing storyline promoting *and* defusing concern for the risks involved. This ambivalence also translates into their daily work, as one interviewee stressed:

> Even our own colleagues have to be frequently told [that] sitting in the middle of a hurricane, one believes everything around to be a storm. But a few meters along, it already ceases. In other words, one has to be careful not to perceive it in too much of a distorted way. (PAO 1)

Such seemingly varying levels of emphasizing space debris as a concern indicate more than mere ambivalent attitudes among space professionals toward sustainability and risk. Instead, we understand them as a way of coping with the ambivalence that comes from dealing with orbital-planetary concerns as inherently related.

This became particularly visible in the metaphor of the "eye of the storm," that one interviewee used to refer to space debris as a concern that encompasses both Earth *and* its orbital surroundings. He implied that, while fearing an engulfing "storm" (space debris encircling Earth) might be sensible for those caught within it (the planet's inhabitants), their concerns should be regarded as highly situated, locally and temporally, rather than of global significance. From the outside of such a storm, PAO 1, the space agency engineer suggested, the risk it poses might turn out to be much more limited and accessible to rational judgment. He implied that those concerned with space debris would thus need to assume a dual perspective: one as being subjected to the risk emanating from space debris through its potential impact on the ground or operational satellites in orbit and one as outside observers to such a threat. This dual perspective seems to point to a transgression of "inside" and "outside" epistemologies of concern that mirror the orbital-planetary challenge posed by space debris.

This interpretation is also supported by our interviewees repeatedly referring to broader storyline of sociotechnical risks and the adverse effects of contemporary ways of living on the environments we live in, as the following quote shows. PAO 2, a space agency lawyer, referred to space debris as an encompassing worldwide challenge to sustainability:

> The problem is that there are no borders up there. And even if only two states or two private companies or even just one produce extreme amounts of debris, this ultimately affects all others or most others that want to use the orbits. It is a global problem in the truest sense of the word [. . .] because the orbits just go around the Earth. (PAO 2)

With this storyline, he linked concerns about space debris to broader, global scale sustainability discourses such as those addressing climate change and marine debris. However, this quote also shows how space debris is not only seen as an impactful sustainability concern but also recognized as material heritage of human spaceflight activities in a global sense—precisely because it questions the notion of global concerns being confined to planetary environments alone.

Responsibility for Space Debris

In framing it as a concern, space sector professionals thus aim to draw attention to space debris as a phenomenon that calls for taking on responsibility beyond the planetary scale.

A recent key objective of the European space sector, as SE 1, the engineer-entrepreneur, outlined, is the "transfer of environmental protection as a goal that we know on Earth and by now consider normal to spaceflight activities" (SE 1). Using analogies like environmental protection, he framed responsible action toward outer space environments as a sustainability challenge similar to those evoked in Earthly sustainability discourses.

Another interlocutor elaborated on this argument further when stating that "over the decades, actually very, very few have added to the problem, meaning really just those that have actually conducted spaceflight activities for decades—a handful of nations that now slowly grows" (PAO 2). He understood this unequal contribution to pollution as "[. . .] an analogy to the issue of climate change, greenhouse gases, etc.," where "industrialized nations have emitted CO2 for 150 years and now want to instruct developing countries what they have to do" (PAO 2). According to PAO 2, like with other sustainability challenges, commercial actors and emerging space nations who are just beginning to use satellite infrastructures would mostly reject to take on responsibility for the material legacies of previous spaceflight activities. Many interviewees stressed that the Old Space actors—nation-states and their space agencies such as NASA and Roscosmos—should take the lead in removing space debris. At the same time, they argued that it would be necessary to enforce more responsibility on the current space debris producers, including commercial New Space companies. One interviewee with a background in engineering and space agency management made this point particularly clear by drawing on the comparison with climate change:

> We need to, in a way, impose "polluter pays"-regulation. Meaning: You want to pollute—you pay the cleaning. And we are not there yet. "Polluter pays" is something that industry doesn't like because they say "it will impact my business, and I have to consider the cleaning up in my business plan." I'm sorry—you have to! [. . .] It's all this . . . like climate change again. If we go back . . . it's somewhat the same story. (PAO 3)

Referring to the intensified economic usage of orbits in the New Space age, another interlocutor stated that she is "not so much concerned about the space debris that they will create, but about the sheer number of operational payloads [satellites] they will create" (PA 1). Alluding to future obligations toward these new satellites and the space debris they eventually might turn into, she strongly emphasized the material-infrastructural continuity of space debris as a matter of responsibility. Precisely because near-future risks through debris are already materially present in the ever-growing numbers of commercial satellites envisioned today, sustainability seemed to strike her as an immediate concern.

One reason for this is that satellites are not only almost always at risk of being destroyed by their nonfunctional predecessors that have turned into space debris. Rather, they also already represent a threat-to-be for future satellite networks. Under these conditions, functional satellites become indistinguishable from space debris in terms of their material quality as "risk objects." In this regard, orbital-planetary infrastructures differ from traditional terrestrial infrastructures that *turn* into risks only by a linear process of decay and neglect (Tutton 2020; Graham and Thrift 2007; Denis, Mongili, and Pontille 2015). In contrast, satellite networks and space debris constitute two sides of the same infrastructural coin, as they are both agents of destruction and subject to infrastructural breakdown.

In that sense, notions of orbital-planetary responsibility often clash with institutions, practices, and materialities of previous decades of spaceflight activities as they become reconfigured due to the economization of space activities in the New Space age. On the one hand, our interviewees stated that orbital-planetary environmental sustainability is negotiated through institutional legacies and their respective responsibilities toward human material heritage in outer space. They framed spaceflight activities of previous decades as clashing with the New Space paradigms' more economically driven approaches. On the other hand, many interviewees considered an increased responsibility for space debris as key to ensuring the sustainable use of Earth's orbits vis-à-vis an economically driven governance of outer space and increasingly crowded orbits. In the following quote, SE 1, the engineer-entrepreneur, anticipates such shifts in how responsibility is enacted:

> Who is going to take responsibility for this? Maybe something will arise out of this "New Space thing." That once big money enters the sector—that they will, out of self-interest . . . "Hey, we now have 100 billion up there. We now

> spend one billion to protect those 100 billion." It is possible that something along this way might happen. (SE 1)

This interviewee concluded that financial self-interest might motivate New Space companies to take responsibility for space debris mitigation, as their own defunct satellites might at some point threaten the future sustainability of the outer space environments they depend on commercially. Even if outer space becomes more and more a place of economic competition, as PAO 4, a space agency engineer and manager stressed, it would be a limited common resource:

> We have one problem. That to launch satellites . . . it gets easier. It means more people launch; there are more satellites. We are creating more garbage in space, so space debris. And it is very quickly within a few years that we are getting to a state where we cannot operate anymore because we have so many satellites in the near-Earth [orbit] that you cannot even launch anymore. You have no place in space anymore. (PAO 4)

This notion was taken up by another interviewee, who underscored that space debris is not only affecting those actors with stakes in the form of established satellite infrastructures. Instead, he stressed that all stakeholders, even future ones, should be equally responsible for sustaining outer space environments:

> Who, in my view, now also bears responsibility, is someone who launches his very first satellite in 2019 and does not care about the problem, even if he is launching his very first satellite saying "I don't care—I pollute." This person bears responsibility, too. (PAO 2)

This statement connects orbital-planetary sustainability to discourses of stakeholder-based responsibility for the commons: an idea frequently used to address planetary issues of environmental responsibility yet not univocally shared within the global space community. Especially US New Space actors often understand outer space sustainability as the ability to engage in the long-term human colonization of other planets, thereby rewriting or even opposing terrestrial concepts of sustainability (Valentine 2012).

In the case of European space professionals, we observed that attributing responsibility for space debris was seen as key to sustaining orbital-planetary environments as a common good. As IN 3, a space industry Public

Relations official mentioned, responsible action toward space debris mirrors the need for environmental protection on Earth.

> I think space plays an important key role in the global world for understanding the environmental impact that we have. [. . .] If you have too much debris in there, we will kind of destroy that resource. So for me to use kind of the same terms that we do when it comes to the environment is pretty easy. But, of course, I've heard . . . . I mean people talk [about] it from a political and geopolitical kind of view as well. (IN 3)

In addressing space debris as a global concern, she described it as embedded in orbital-planetary interactions that shape societies' perception of sustainability. She implied that outer space environments enable a global perspective on human "environmental impacts" in a twofold way. First, by rendering visible the human environmental impact on Earth itself—amply documented by satellites in orbit. Second, by pointing to space debris' role as not only disrupting global satellite networks surveilling planetary environments but also polluting outer space itself. In that sense, space debris here emerges as an infrastructure that "transcends its regional context to connect with other systems and gains national or global reach" (Henke and Sims 2020, 12)—for example, regimes of Earth observation and "geopolitical" concerns, as mentioned by IN 3.

Representing Infrastructure: Space Debris as Elusive Materiality

In the previous section, we have shown how interviewees enacted orbital-planetary relatedness by crafting storyline of space debris as a sustainability concern demanding responsible action. In this section, we trace how interviewees engaged with visual representations of space debris as a second site of coproducing orbital-planetary sustainability as an overarching concern.

Visualizing Concern through "Orbital-planetary Clouds"

Space debris is often visually represented as what we want to call "orbital-planetary clouds" (see Figure 1). These are computer-generated images that follow a distinctive and mostly uniform principle: They depict planet Earth surrounded by myriads of small, pixel-sized dots meant to represent space debris in orbit. The planet itself and the cloud-like orbiting

Figure 1. Example of an "orbital-planetary cloud" as visualized by the European Space Agency (European Space Agency 2019).

rings or spheres of debris sharply contrast the vast, black background of outer space.

Throughout our interviews, it became apparent that this orbital-planetary cloud-style of visualization is highly charged with meaning. One interviewee remarked that the computer-generated visualizations he and his colleagues create contrast standard representational practices displaying Earth as a singular, pristine yet fragile place in the vastness of outer space. According to PAO 1, these visual representations

> simply show this beautiful planet Earth and its surroundings—the Moon and the Sun—and one simply marvels at this great vastness like astronauts that, for example, take pictures of Earth and tell the story of a very beautiful blue sphere. But otherwise, there is really not much to see in these pictures. Then we come along with our animations and bring in all these—well, at the moment, there are about 30,000 dots [. . .] suddenly orbiting the Earth.

While initially referring to Earth as an untainted "natural marvel" represented in such imagery, the interviewee pointed to what he sees as a disturbing contrast: the awe-inspiring representation of the planet being tainted by depicting space debris surrounding it.

This ambivalence in visualizing space debris as a source of irritation points back to the representational practices of the Old Space age. For instance, the "Blue Marble" picture taken by astronauts of the Apollo 17 mission in 1972 memorably depicts an encompassing global view of Planet Earth, surrounded by the dark vacuum of outer space. As Jasanoff (2001) notes, it "symbolizes planetary togetherness," but also "ironically undermines its own authority [. . .]. It promises an imagined community as encompassing as the Earth itself, but is this a community in which those without the power to patrol the heavens, to map and perhaps to devastate the Earth, can ever meaningfully participate?" (335). This question translates to the "orbital-planetary cloud"-type of visualizations as well, as these challenge the imagery of planet Earth as a confined space for humanity and instead reinforce the extension of power asymmetries to impact environments beyond the planet: those actors able to launch significant numbers of satellites in the past shape visual planetary imaginations today. "Orbital-planetary cloud"-style visualizations make particularly clear that power not only extends beyond the boundaries of the planet but is also inherently linked to the material agency of orbital-planetary environments—hybrid spaces that are constituted by space debris and at the same time threaten critical satellite infrastructures. Although many interviewees expressed a certain sense of unease with these representations, they saw them as necessary depictions of a severe challenge. A challenge that "is difficult to get your hands on. It's . . . for most people, it's literally far away. In Dutch you say 'it's far away from my bed'" (PA 1), as one of them, the space policy advisor and space activist, explained. As a representational practice, orbital-planetary clouds aim at disrupting the established visual narrative of planetary limits of the "Spaceship Earth," which has supported the perception of outer space as far removed from planetary concern.

Scaling Visualizations: Space Debris as a Boundary Infrastructure

"Orbital-planetary clouds" represent the planetary environment and its inhabitants as inevitably surrounded by their infrastructural remains. As IN 2, a space insurance professional, remarked, they are "very easy to spot or visualize—looking like a ring originating in nature, revolving around us. Despite it being anthropological [sic!]" (IN 2). As visual representations, they create a sense of urgency, as this interviewee pointed out:

> One recognizes the effect that this whole thing has. That suddenly, this whole anthill of debris is revolving around our Earth—looking considerably worse

> in these animations than it actually is. [. . .] This conveys quite a bit, I think, . . . that we suddenly see that all that revolves around Earth was brought there by us and most of it is no longer functional. (PAO 1)

The ontological uncertainties inherent in the "orbital-planetary clouds" sometimes raised discomfort among our interview partners, who were often hesitant to represent the visualized debris as nothing more than technological residue. After all, it appears to constitute an outer space environment well beyond planetary scales—an assemblage that has claimed a territory beyond Earth as its own. However, the thoroughly artificial origin of space debris' materiality can hardly be naturalized. Thus, demarcations of "the natural" and "the technological" often called upon in earthbound sustainability discourses seem somewhat problematic when projected to beyond-planetary scales.

This is especially the case when applied to orbits as ontological transition zones demarcating Earth from outer space. Like this agency official, interviewees engaged in creating visualizations were concerned about the potential impact of scaling frames of reference for space debris:

> These images that you often see, that also we ourselves distribute . . . with these white dots. [. . .] This is, of course, graphically distorted because once you get the Earth as a "big something" on a piece of paper and put those dots around it, each dot is massively over-scaled. If you would do it to scale, meaning the correct relative size, you would see nothing. After all, these are screws flying through outer space. But I do not want to downplay or trivialize it. It is a problem. (PAO 2)

Expressing his unease with the fact that dots representing debris are usually visualized disproportionally large in computer-generated images of space debris in Earth's orbit, he worried about the potential misrepresentation of the magnitude of the challenge posed by space debris. At the same time, realistic scales would make visualization impossible, as PAO 2, the space agency lawyer, stated.

Regarding what they see as potential misrepresentation, our interlocutors found themselves confronted with contradictions regarding their practices of infrastructural boundary work, in that visualizations of "orbital-planetary clouds" do not allow them to localize infrastructural risk to planetary or orbital environments alone. Visually suggesting planetary intactness, to them, would negate the tangible presence of space debris as a material risk. Representing space debris by myriads of dots, on the other hand, would

immediately render debris as a concern relevant not only to outer space affairs but also very imminently to terrestrial societies.

Here, our interlocutors' constant struggle with the decreasing plausibility of representing planetary and orbital environments as separate became visible. To them, space debris constituted a challenge that can neither be represented as fully terrestrial nor as situated in outer space alone. To raise awareness of space debris as a concern, they saw no alternative to constantly visualizing it as an inherently multisited "disturbance." As a boundary infrastructure, space debris thus appears to enable what Olson and Messeri (2015) have called "scalar politics of cosmologies" (p. 31). As it requires speaking of orbital-planetary environments by always referring to a multitude of scales, it also mirrors what Gärdebo, Marzecova, and Knowles (2017) define as an interscalar vehicle: An "empirical object [. . .] that simultaneously occup[ies] different political, ethical, epistemological, and affective scales and contexts that are usually 'kept apart'" (Gärdebo, Marzecova, and Knowles 2017, 45).

Conclusion

In this article, we have shown how the material relations of orbital-planetary environments came to matter in the storyline of European space sector experts and how they constructed space debris as an orbital-planetary challenge. From a co-productionist perspective, and in conjunction with the concept of boundary infrastructure, we traced the discursive and representational practices through which these experts enacted orbits as parts of orbital-planetary environments and space debris as the material infrastructure inhabiting them. We focused on discourses and representations, as this conceptual and methodological choice allowed us to trace how interviewees "talked about" space debris as a hard to grasp infrastructural phenomenon. It also helped us to account for visualizations as a significant part of discursive practices within our material.

Specifically, we attended to those storyline and visual representations by which space sector professionals attempted to establish a common ground for relating to orbital-planetary concerns and beyond-global scales of sustainability. Through these storyline, and by relying on metaphors from broader environmental discourses, interviewees aimed to raise awareness of space debris risks in unsustainable orbital-planetary environments. Regarding representations, we identified visualizations of "orbital-planetary clouds" of space debris as a critical point of reference for interviewees in (re)scaling orbital-planetary environments.

We conclude that, not unlike the oceans, outer space has long been conceived as infinite. Accordingly, the emerging awareness of space debris as a sustainability concern has only recently led to novel ways of thinking about matter, responsibility, and sustainability as coproduced beyond the planet—as a sociotechnical risk and side-effect of our lifestyle on the environments we occupy. In the advent of the economization of space activities in the New Space age, notions of responsibility become increasingly reconfigured in the space community. They seem to clash with the institutions, practices, and ideas of previous decades of spaceflight. In a sense, today's crowded orbits and the growth of space debris resemble the well-known tragedy of the commons (Hardin 1968; Damjanov 2017). This is as those performing spaceflight continue to pollute a common good without—individually and collectively—taking responsibility for developing more sustainable ways of using the shared resources that outer space provides.

We suggest that understanding space debris as a boundary infrastructure is a first step in acknowledging how it (con-)tests the traditional demarcations of orbital and planetary environments. Unlike many other infrastructures, space infrastructures always incorporate the material source of their future demise in the form of space debris, as the risk environment created by space debris proliferates the decay of further space infrastructure. At a certain point in their life span, orbital-planetary infrastructures transition from infrastructure at risk to *putting* at risk other infrastructure. Unlike other artifacts, for example, consumer objects, which typically meet their end by engineered obsolescence, extensive use, or destructive external influence, space infrastructures are at once the immediate cause and victim of breakdown. This characteristic of space debris as an inherent sustainability risk calls for further explorations of currently ongoing satellite launch activities by private space ventures. As New Space actors and policy makers alike support launching unprecedented numbers of new satellites into orbit, humanity actively and knowingly continues to generate unavoidable future threats today.

However, similar to other forms of human-made waste, such as micro-plastics in global ecosystems (Schönbauer and Bergmann 2019), we are now witnessing a shift in how these once accepted by-products of technoscientific progress, economic interests, and geopolitical relations increasingly become matters of public and political concern. Regarding space policy, a new epistemic and political relatedness of orbits and planetary concerns is established through the enhanced awareness of space debris as a boundary infrastructure. This poses novel questions about the responsibility for the space technologies' material legacies and possible forms of

orbital-planetary care. These have not been paid considerable attention throughout the twentieth-century space age in which the sustainability of outer space environments has received only marginal attention.

Space debris is not a distant outer space phenomenon but rather in many ways closely bound to planetary concerns; as a boundary infrastructure, it connects envisioned futures of space exploration and exploitation to their material technopolitical legacies. Utopian imaginaries of colonizing Mars (Tutton 2018), for example, remain clouded by the potential risk of debris. Future work at the intersections of STS and SSOS appears well suited to explore the material enactment of orbital-planetary infrastructures as a means to understand sociopolitical sustainability discourses in techno-societies at large.

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Notes

1. In this context, policy makers and space experts regularly evoke the notion of the so-called Kessler syndrome. It describes a scenario of cascading space debris collisions and thus self-multiplying debris fragments leading to increasing orbital pollution. The term is proliferated within the space community referring to a paper published by Donald Kessler, a National Aeronautics and Space Administration scientist, in 1978. This paper is considered to be one of the first published systematic accounts of long-term sociotechnical impacts of space debris.

2. The references of each quote in the empirical part provide more detail on interviewees' respective affiliations: Policy Advisor (PA), Public Administration Official (PAO), Industry (IN), and Space Entrepreneur (SE). We also mention professional and disciplinary backgrounds of interviewees within our analysis.

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