Editorial

Dawn of space tourism: It is time to address the environmental impact of anthropogenic debris upon above earth

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Abstract:

More than 8,000 tons of orbital debris have been generated from human space missions. Previous studies are mainly concerned about collisions related to space debris, while discussions are very scarce on their impact on earth's environment. Here, we present a compilation analysis of existing evidence and theories on the known and potential impact of space debris on earth's environment. Specifically, man-made space objects and debris have increased light pollution on earth by about 10%, where the zenith luminance reached to approximately 20 μcd m^{-2}. Some space debris consumes ozone and releases carbon dioxide and other chemicals as they are burned, resulting in the cooling and shrinkage of the thermosphere due to excessive heat shedding via infrared radiation. Meanwhile, the solid and liquid propellants used in rocket launching may pollute earth's atmosphere and deplete stratospheric ozone. In addition, fall-off nuclear-powered rocket engines and parts can cause large-area radioactive pollution by shedding nuclear fuels and debris. Some countries and institutions, including China which recently completed its first rover landing on Mars, have issued mitigation guidelines for orbital debris, with limited success to date. The humankind will not slow down their pace in exploring the universe. Notably, space travel companies such as Virgin Galactic, Blue Origin, and SpaceX all launched their space flights earlier this year to meet the emerging demand for untrained earth citizens to venture into space for leisure. With the intensifying activities in space missions and tourism, it can be anticipated that more space flights will take place in the near future, with more rockets, satellites, spacecraft, and inevitably debris left in the orbital space upon earth, casting an increasing impact with potential threat to earth's ecosystems. We call on global leaders and researchers to take actions to mitigate the unintended impact of space debris on earth. Meanwhile, new technology and engineering advancements such as reusable and clean energy-fueled rockets can drastically reduce orbital debris generated from space missions.

Keywords: Space debris; light pollution; atmospheric pollutant; radioactive waste; space travel

1. Introduction

Humanity has continuously made progress in space expedition. The year of 2021 has been a particularly busy year for the red planet. The U.S. National Aeronautics and Space Administration's (NASA) Perseverance rover program (NASA 2021a), United Arab Emirates' Mars Mission (UAESA 2021), and China's Zhurong rover (CNSA 2021) all marked new achievements in space exploration by the humankind. As humorously put by John Bohannon, '*Humans are messy, and not just here on Earth*' (Bohannon 2015), anthropogenic wastes have become the common human footprints from those missions. Space debris, also known as space junk or orbit debris (Chepkemoi 2019), refers to all kinds of abandoned wastes left in cosmic space (**Fig. 1**), including discarded or out of control spacecraft, fuels, parts, and wreckages (NASA 2021b). Since humans started launching artificial objects into space in the 1950s, space debris has continuously spawned and accumulated (Lawler 2011; Staughton 2020). So far, over 5,250 space launches have been successfully completed, producing an orbital wasteyard composed of approximately 23,000 objects large enough to be detected with a total weight over 8,000 tons (NASA 2020; NG 2019), which escalates at 2%–5% annually (**Fig. 2**) (Witze 2018; Dekorsy et al. 2017).

Despite the recent attempts (Forshawa et al. 2020; Pultarova 2018), there is no practical method to clean up space debris on a meaningful scale. As a constant risk factor for outer space safety, this aggravating issue has raised emerging concerns by the United Nations (Crowther 2002; Schaper 1999), the European Commission (Clery 2020), and countries actively engaging in space exploration missions including the United States, China, Japan, and Switzerland (Clery 2012; CNSA 2016b; Loomis 2015; Normile 2016). Previous studies and scholarly discussions, however, have centered on the risks of collisions caused by space debris in orbits. According to a recent estimate by NASA, there are approximately 23,000 pieces of debris larger than a softball orbiting the earth, travelling at speeds up to 17,500 miles per hour (*ca.* 7.8 km per second), which is fast enough for one small piece of orbital debris to catastrophically damage a satellite or a spacecraft (NASA 2021b). In 1996, a French satellite was hit and severely damaged by the debris shed from a French rocket that exploded a decade earlier (NASA 2021b). The risk of space debris-induced collision was vividly depicted in the 2013 blockbuster film, '*Gravity*', which raised public attention on space debris as a prominent safety threat for astronauts working in international space stations. In the meantime, there have only been anecdotal discussions on the potential impact of space debris on the earth's environment and ecosystems (Graham 2021; Sokol 2021; Staughton 2020). Here we provide a concise review on the evidence and scholarly opinions on the impact of space debris on the ecosystem on earth, covering light pollution, atmospheric pollution, spread of radioactive wastes, and other impact by scrutinizing existing evidence as well as new hypotheses recently put forward in scientific literature.

2. Light pollution

The International Astronomical Union recommended that astronomical observatories should only be established where the amount of light brought by light pollution to the natural sky glow does not exceed 10% (Sokol 2021). A recent study suggested that places available for viewing stars without light pollution from orbital debris and other man-made objects seem to be vanishing on earth (Sokol 2021). Space debris typically travels at an altitude of 500–800 km above earth, although due to frictions, approximate 80 tons of the debris will enter earth's atmosphere, travel into the thermosphere (1000–2000 ℃), and stay at a lower altitude

(320–480 km) (Lemaître 2019; Staughton 2020). Part of the space debris traveling through the atmosphere will combust spontaneously (NASA 2010; Crowther 2002), although some aerospace materials burn incompletely due to their high melting points (e.g., >1000 ℃). Incompletely burnt debris may generate fine particulates, paint flakes, and solid propellant particles when colliding with each other or due to frictions with the atmosphere when moving at high velocities (ESA 2020). Once released into the atmosphere, these components reflect and scatter light, causing light pollution (**Fig. 1**) (Graham 2021; Kamenev et al. 1997; Kocifaj et al. 2021; Sokol 2021; Staughton 2020). One study estimated that diffused light increased by about 10% due to objects and debris in the orbit (Sokol 2021). Preliminary estimates from the IAU suggest that this additional source of light pollution increases the zenith brightness to about 20 μcd m^{-2}, the threshold for light pollution obstructing astronomical observatories (Kocifaj et al. 2021).

3. Air pollution

Like the 'ozone hole', changes in the upper atmosphere have significant impact on the environment and climate on earth (Laštovička et al. 2006). As early as in 2010, NASA warned that the upper layer of the earth's atmosphere had shrunk abruptly in just four decades, which had abnormally low densities that were about 30% lower than previous contractions on record since 1967 (Derrick 2010). Studies showed that, unlike in the lower atmosphere, carbon dioxide (CO_2) acts as a 'coolant' in the upper atmosphere on earth, constantly shedding heat via infrared radiation. As carbon dioxide levels build up on earth, it makes its way into the upper atmosphere and magnifies the cooling effect during the 'solar minimum' (Derrick 2010; Laštovička et al. 2006). There are three known sources of carbon dioxide in the thermosphere, namely, from the earth's surface, emissions from fuel combustion during rocket flights, and the combustion of space debris in the thermosphere. Further, some metals and polymers in the orbit undergo chemical reactions when burning through the atmosphere, depleting ozone and generating carbon oxides and nitrogen oxides in the thermosphere (Staughton 2020) (**Fig. 1**). Further, metallic debris such as tungsten, beryllium, aluminum may also undergo chemical reactions when they re-enter the atmosphere, and their impact on earth's atmosphere is also worthy to research (Physics Today 2009). Also, emissions from solid fuels and liquid propellants during rocket launches can cause pollution in the atmospheric environments, of which the depletion of stratospheric ozone is the most studied and concerning issue (Dallas et al. 2020).

4. Radioactive wastes

Shedding of nuclear-powered engines and fuels often cause radioactive contamination on earth. As of 2005, at least eight radioisotope thermoelectric generators, 13 nuclear reactor fuel cores, and 32 nuclear reactors were still circling the earth in orbits below 1,700 km (WISE 2005). The United States and the former Soviet Union had about one ton of uranium 235 and other nuclear fuels in their nuclear reactors orbiting in space around the earth (Bunn and Holdren 1997; WISE 2005). Two nuclear-powered reconnaissance satellites launched by the former Soviet Union brought radioactive pollution to earth surfaces. In 1978, a multitude of radioactive debris from 'Cosmos 954' fell into earth's atmosphere and spread over large areas in Canada, where about 30 kg of enriched uranium on the satellite, reactor wreckages, and radioactive debris spilled on a ground path stretching over a distance of 600 kilometers, causing serious radioactive pollution (SL 1981; Rich 1978; DiaNuke 2020). In 1983, the nuclear reactor core of 'Cosmos 1402' fell into the south Atlantic ocean (Leifer et al. 1987; Rich 1983). About a year later, a series of aerosol samples were collected at altitudes between 27–36 km using high-altitude balloons in order to track and ascertain the whereabouts of the reactor core. U(235) concentrations were found to be higher than background levels by 53 ± 20% at an altitude of 36 km, and the total excess of U(235) was estimated to be 44 ± 15 kg in the stratosphere (Paddy 1983; Leifer et al. 1987). Here, a dreadful scenario exists in that nuclear reactors and radioactive materials will spread and continue to pollute the atmosphere for many years after the life of the satellite ends (Levi 2007). Further, the unrestrained nature of orbital debris means that these radioactive materials may fall into populated areas on earth at unpredictable timing (CNBC 2021).

5. 2021: Dawn of space tourism

When Russian astronaut Yuri Gagarin became the first human to journey into the outer space, no one would think that ordinary people could, one day, venture into space for leisure (AIT 2021). A series of recent events may have marked the dawn of commercial space travel, or 'space tourism', aided by the remarkable advancements in astronautics and engineering in the past few decades. In addition to professional astronauts, untrained earth citizens have traveled into space since the beginning of the new millennium when Dennis Tito, an American businessman, became the world's first orbiting space tourist in 2001 (Wall 2011). The Russian Space Agency put seven paying customers in space between 2001–2008 (Messier 2021).

The race to space accelerated abruptly in the year of 2021. Virgin Galactic, a US-based space flight company, demonstrated the readiness of its air-launched spaceplane for ticket-paying passengers by completing its first suborbital test flight with VSS Unity, a rocket-powered spaceplane (Malik 2021). On July 11, 2021, the VSS Unity successfully delivered a group of space tourists to the edge of space using a hybrid propellant comprised of hydroxyl-terminated polybutadiene, a solid carbon-based fuel, and nitrous oxide, a liquid oxidant (VG 2021). The combustion of these fuels could produce greenhouse gases and air pollutants, which can last at least two to three years in the atmosphere (AIT 2021; Marais 2021). Nine days later, four citizens including Jeffrey Bezos, the founder of Amazon.com, took the New Shepard rocket launched by Blue Origin, a private space tourism company founded by Bezos, for a short space trip by passing the Kármán Line, the internationally recognized boundary of earth's atmosphere and the outer space, and safely returned (BO 2021). Not to be outdone, SpaceX announced its schedule to offer 4–5 days of orbital travel using its Falcon series of reusable rockets to propel its Crew Dragon capsule into the orbit, using liquid kerosene and liquid oxygen (Marais 2021). On September 18, 2021, the Dragon and the Inspiration4 originated from the SpaceX was successfully launched by its Falcon 9 rocket and finished the first commercial manned space mission by sending four ordinary citizens into space for a three-day space tour and safely returned off the coast of Florida, with its $200 million costs paid for by others (SpaceX 2021). This was the first time in history that humans ever completed an orbital mission without professional astronauts, reaching another milestone in commercializing space travel (SpaceX 2021).

These highly publicized events of individuals traveling to space for leisure and the much lowered costs of space flight owing to technological advancements have sparked worldwide interests in the possibility of mass space travel by earth citizens (Reeve 2021). Industry insights suggest that space tourism could be worth more than three billion dollars by 2030 (Reeve 2021; Sheetz 2019). Meanwhile, criticism has also been raised with respect to the environmental impact of those extremely costly and energy-intensive leisure activities (Bohannon 2015). Sitting at the dawn of space tourism, it is important to establish international conventions and regulations and invest in new technology developments to minimize anthropogenic debris and pollutants generated by those activities that are often left for decades in earth's atmosphere and orbital space (Sheetz 2019) and ultimately, to aid in the sustainable growth of the emerging space travel industry.

6. Past efforts and a path forward

To date, NASA, the European Space Agency, and China have issued mitigation guidelines for orbital debris (NASA 2011). In March 2020, the United States Space Force proposed the use of 'Space Fence' to track space debris, which can detect 20,000 objects a day and track 200 near-Earth debris simultaneously (Mizokami 2020; LM 2020). Earlier to this, the 'ClearSpace-1 mission' (ESA 2019), the 'space harpoon' (Pultarova 2018), and other initiatives were proposed by the European Space Agency to clean up space junk. In these proposals, the first step was to capture space debris and then to push them into earth's atmosphere for incineration (Pultarova 2018). The European Space Agency also planned to send a self-destructing robot into orbit in 2025, which is designed to function as a 'space vacuum cleaner' (NPR 2019). As one of the signatories of the 'Outer Space Treaty', the Chinese government also made a commitment to reduce the production of space debris and invest in space debris clean-up programs (CNSA 2016a). In 2016, China launched the AoLong-1 'Roaming Dragon' satellite, a space-debris automatic cleaning aircraft which was designed to 'grab' space junk orbiting in the space and 'throw' it back to earth's atmosphere for burning, but the results are presently unavailable (Forshawa et al. 2020). Some researchers proposed the idea of using powerful lasers to clean up old satellites and other orbital debris upon earth (Wen et al. 2018). These impressive proposals, however, faced significant technological or financial obstacles. It is also much better to control the source of debris generation than to clean up the debris once it is left in space. So far, recyclable rockets are the only proven option of reducing debris generation from space missions. Designed and manufactured by SpaceX in 2010, the Falcon 9 is a reusable two-stage rocket that is designed to transport people and payloads into the earth orbit and beyond. In the long term, using reusable rockets and spacecraft with clean hydrogen-based fuels will fundamentally address the problem of space debris generation in future space missions (Spacex24 2020).

Empowered by new technological and engineering advancements, humans will continue to explore the universe in the coming decades, and perhaps in a more aggressive and frequent manner. Orbital debris can be extremely persistent, is difficult to remove once it is there, and is continuing to be added every year, creating 'stock effects.' (**Fig. 3**). Launch rates of space objects reached around 110 per year in 2020, with annual break-ups continuing to occur at average rates of 10–11 per year (ESA 2020). With the current enthusiasm in space exploration and more countries wanting to join the race in a near future, the number of debris objects in space is set to increase (ESA 2015, 2020). That means more fuel rockets, satellites, spacecraft, and inevitably, debris will be abandoned in orbitals and outer space surrounding earth. There is already ample evidence on their impact on earth's environment, and their rapidly increasing quantities also pose a prominent threat to the safety of astronauts working in space stations and perhaps the future generations of mankind entering or living in space, which will become more difficult to navigate through. It is time for us to formulate a pragmatic, environmentally responsible response to the legacies of past and future human space missions. Along with astronautical engineers, environmental scientists and engineers have an essential role to take in addressing these longstanding issues.

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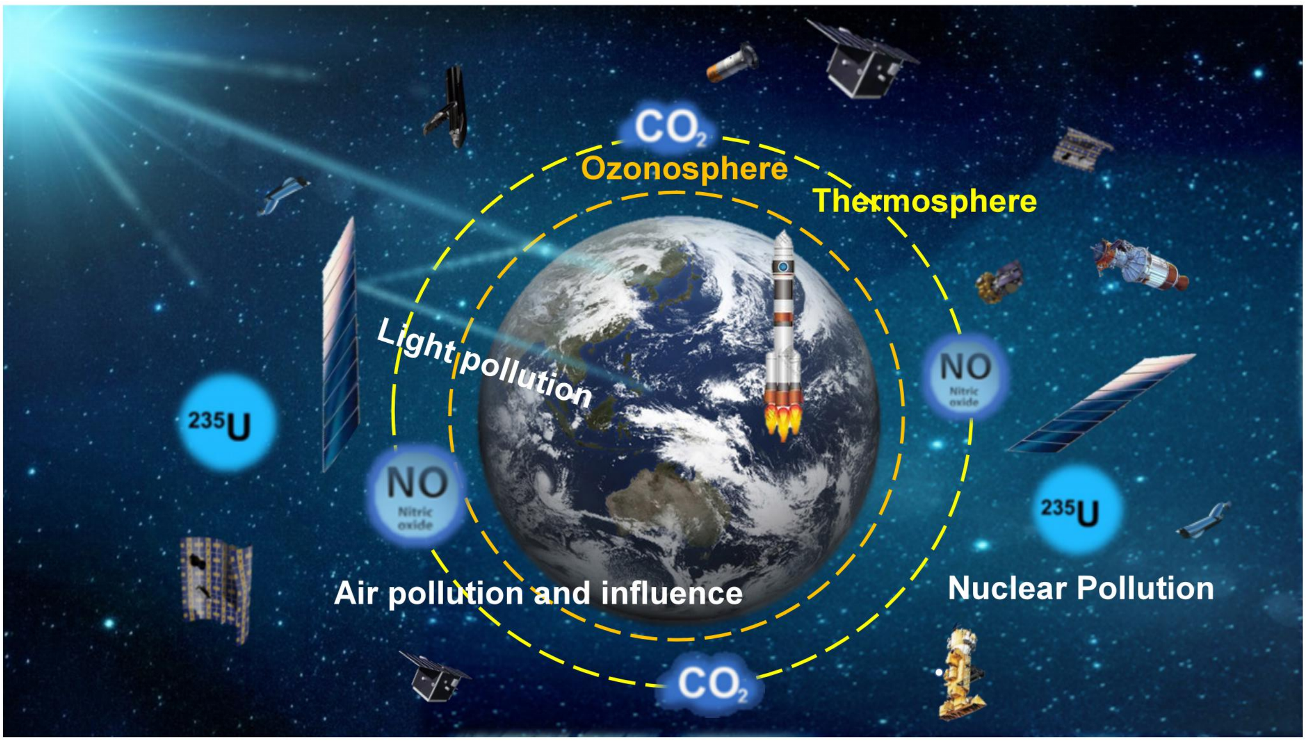

Fig. 1 Man-made objects including space debris have increased light pollution on earth by nearly 10%. Zenith luminance of this additional light pollution source reached about 20 μcd m^{-2} by reflecting and scattering sunlight, resulting in the disappearance of locations on earth suitable for astronomical observatories. Some space debris consumes ozone and releases carbon dioxide or other compounds when it returns to the thermosphere and burns, which leads to the cooling and shrinkage of the thermosphere due to excessive infrared radiation. Solid or liquid propellants used in rocket launching pollute the atmosphere on earth. Although infrequent, radioactive debris have been left in earth's atmosphere from nuclear-powered components in space objects launched decades ago.

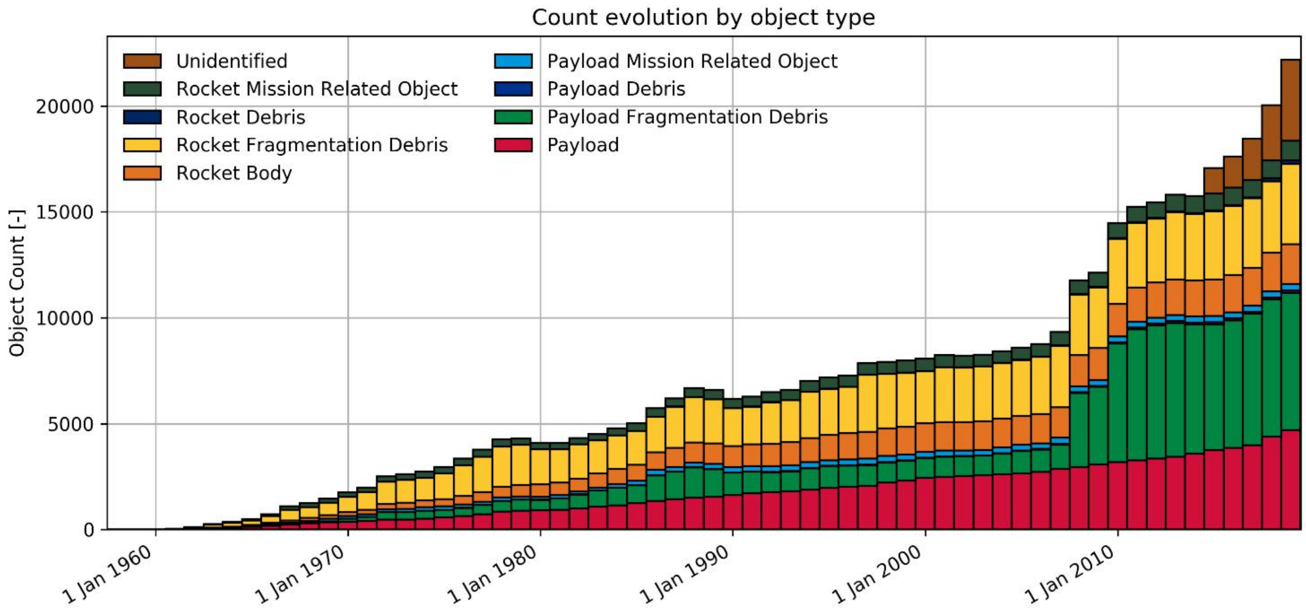

Fig. 2 Since the 1950s, space debris has been increasing every year at an average rate of 2–5% a year. Payload fragmentation debris accounted for the largest category of space debris emerged in the past decade (2010–2020). Adopted from ESA (2020).

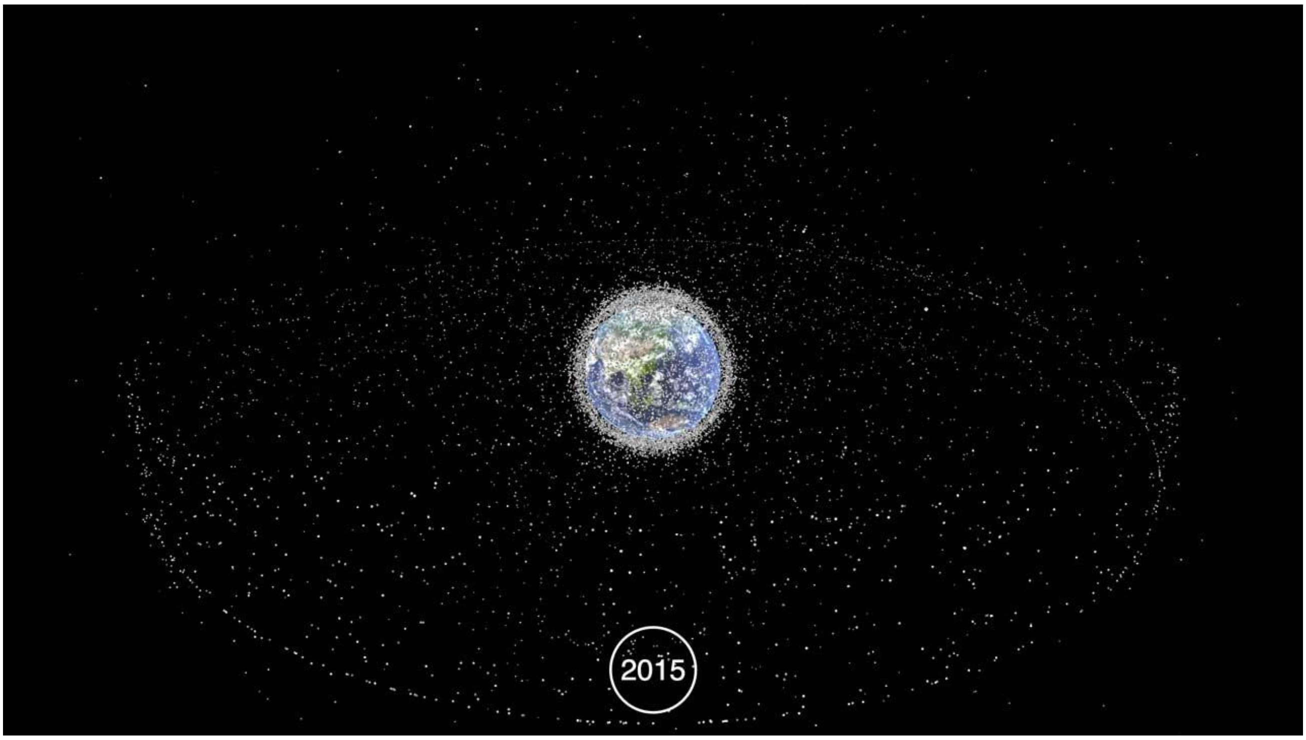

Fig. 3 Snapshot of a data-driven animation of the debris generated from past human space missions (1957–2015) and abandoned in earth orbits and beyond. It is estimated that, as of 2015, there were about 20,000 known pieces of space debris bigger than an apple —traveling at 17,000 miles per hour or faster —making earth orbits and the outer space a very cluttered place. See the full interactive 3D animation at the website maintained by the Royal Institution of the United Kingdom (https://www.rigb.org/docs/debris/). Credit: Dr. Stuart Grey, University College London, 2015.