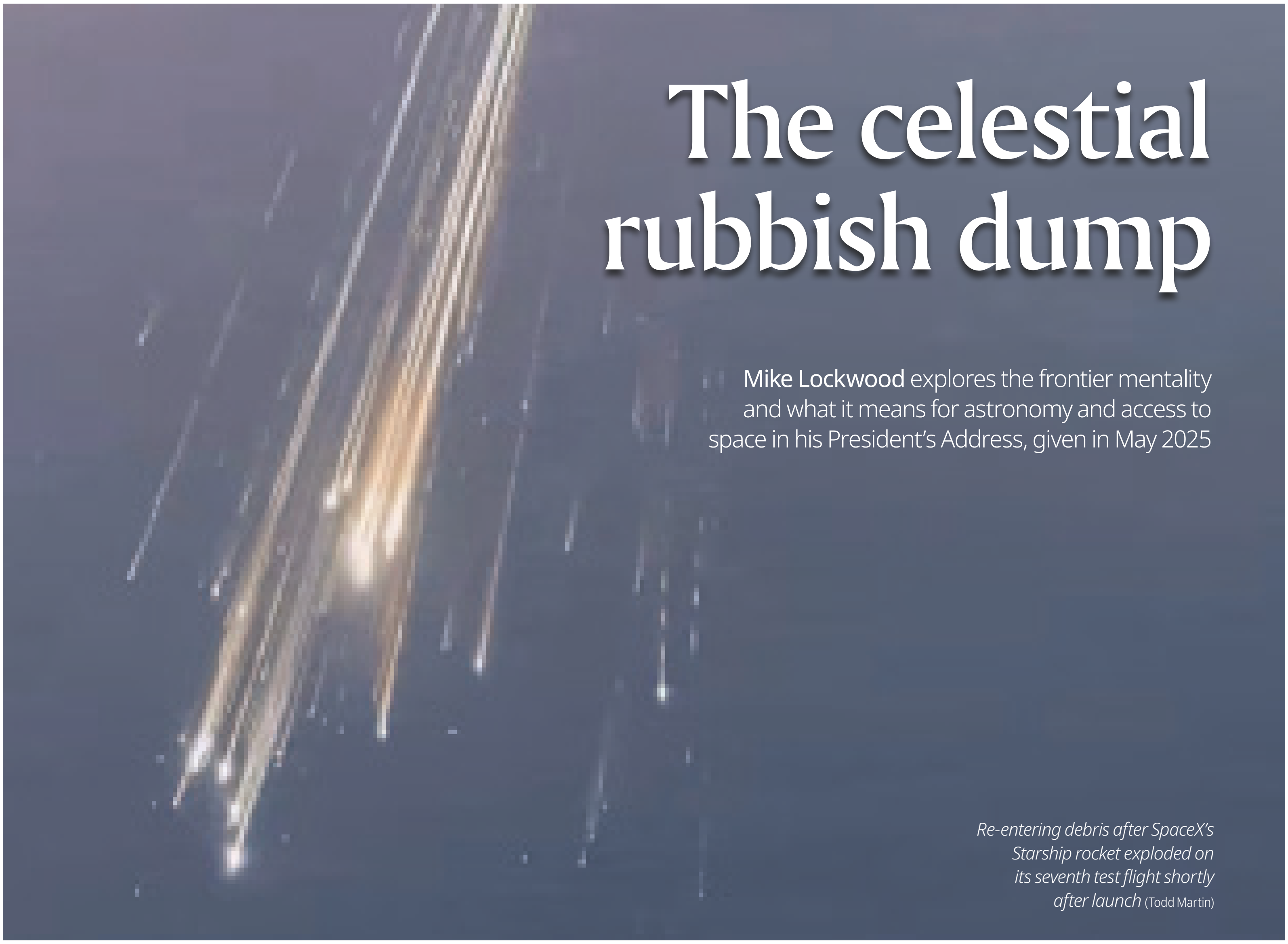
The celestial rubbish dump



Mike Lockwood explores the frontier mentality and what it means for astronomy and access to space in his President's Address, given in May 2025

Re-entering debris after SpaceX's Starship rocket exploded on its seventh test flight shortly after launch (Todd Martin)

"Space: the final frontier…" That brilliant opening to every Star Trek episode is imprinted on the minds of a generation. The scriptwriters were drawing on a mythology of the 'frontiersman' that was established in America by an 1898 essay by historian Frederick Jackson Turner – an idea that gave a unifying social cohesion to America. The romance and adventure of those brave men and women who lived and worked on the boundary between civilisation and the wilderness is not in question. But an important question that remains is: when is a frontier no longer a frontier? More specifically, when has the frontier so eroded the wilderness that the ecosystem services the latter provides to civilisation are threatened? That is a vitally important question because experience shows that applying frontier mentality and thinking where it is not appropriate drives unsustainable and irresponsible behaviour.

Turner also discussed a darker side to frontier mentality not often quoted by those who invoke the mythology of the frontier. In his presentation to the American Historical Association meeting in Chicago on 12 July 1893, he said: "The frontier individualism has, from the beginning, promoted democracy… but it also made that democracy strong in selfishness and individualism, intolerant of experience and education, and pressing individual liberty beyond its proper bounds". Its tendency, he said "was anti-social" and it produced "antipathy to control, and particularly to any direct control. It has permitted lax business honour, inflated paper currency and wildcat banking".

Turner's 'Frontier theory' has been the subject of much debate and other authors have discussed how it promotes unsustainable and irresponsible behaviour. For example, Donald Worster (1979) in his book *Dust Bowl* describes how frontier mentality led to unsustainable farming practices in the mid-west, allowing drought to cause the devastation of the dust bowl years. Patricia Limerick (1987) discusses how it led to immoral and illegal political practices, themes returned to by Carina Keskitalo (2024) who draws a distinction between colonising and conserving frontier mentalities.

I would illustrate the point with the history of the North-American bison. Animal remains show that in pre-history these amazing beasts were found throughout most of the continent, from Alaska to Mexico. It is estimated that they numbered over 60 million in 1800, but by 1900 there were just 354 known. This was more than irresponsible behaviour as it was deliberately unsustainable: the use of soldiers and government payments to hunters betray it as an ethnic-cleansing ploy, designed to remove the livelihoods of the native Americans.

An interesting point is that by 1870, when 6.5 million animals remained, the bison herds were restricted to two areas, north and south of the railroad to the west. The Union Pacific and Central Pacific railways had met at Promontory Summit, Utah in May 1865; although the rate of bison killing was already in decline, there was a peak soon after that led to the near-extinction of the animal. This was because trains travelling between cities in the east and the west coast would stop if they saw bison; railway staff would equip the tourists with a rifle and a cowboy hat so they could leave the train and hunt them. When herds could no longer be

"Experience shows that applying frontier mentality and thinking where it is not appropriate drives unsustainable and irresponsible behaviour"

found near the railroad, agencies sprung up all over America to facilitate wealthy people to find and hunt the rapidly disappearing bison. Photographs from the time show the plains white with animal bones. These people were not frontiersmen in any sense – most of them lived comfortable lives in cities – but they were pretending to be and that pretence was used to justify irresponsible and unsustainable behaviour.

Earthrise

In 1950 the astrophysicist Fred Hoyle gave a series of lectures on the BBC Home Service entitled 'The Nature of the Universe' (the series in which he introduced the term 'Big Bang'). In those lectures he made a comment of truly extraordinary perceptiveness: "Once a photograph of the Earth, taken from outside, is available, once the sheer isolation of the Earth becomes known, a new idea as powerful as any in history will be let loose."

That photograph was taken at 16:39:52 UTC on Christmas Eve, 1968 by William Anders on board Apollo 8. Now classified as NASA image AS08–14–2383, it is better known as the 'Earthrise image' (although Anders actually envisaged it as the Earth appearing from around the side of the Moon rather than it rising). Hoyle was right; I remember well the effect it had on my parents when they first saw it in the colour supplement of their Sunday newspaper: there was our planet, seen to be small and fragile, and in stark contrast to the barren and inhospitable surface of the Moon. Importantly, it was also clearly finite in size and resources. This should have marked the end of applying frontier mentality to Earth's resources. As William Anders commented, "We came all this way to explore the Moon, and the most important thing is that we discovered the Earth".

So if the Earth should no longer be thought of as a frontier, is it responsible and sustainable to see space as a frontier? The answer depends on which part of space you are talking about. The Moon and Mars can legitimately be thought of as frontiers, because settlements there would be on a genuine border between civilisation and a wilderness. However, there are serious physiological, psychological and medical concerns about the reality of sustaining human life and civilisation permanently on either, no matter how much human ingenuity is deployed: these include lethal radiation doses, lower gravity, toxic soil, lack of or toxic atmospheres, highly abrasive dust and extremely low temperatures.

But what about near-Earth space? Low Earth Orbit (LEO), Geostationary Orbit (GEO) and Mid-Earth Orbits (MEO) are already massively important resources for humankind. They are used for communications, navigation, astronomy, Earth observation, resource exploration, disaster management, broadcasting, novel materials production, zero-gravity experiments and many other applications. These near-Earth orbits are no longer a frontier: they are a hugely valuable and increasingly threatened resource and a key part of civilisation. And as this article will discuss, there is a great irony here: abuse of near-Earth space through inappropriate frontier mentality could, in its most extreme form, lead to an effective cage of space junk that could make it unacceptably dangerous or, more likely, prohibitively costly to get humans to the true frontiers of other parts of the solar system.

History shows that the Earthrise picture, despite promoting environmental thinking, did not mark the end of applying the frontier myth to human affairs.

"The problem for the self-proclaimed keyboard- and boardroom-frontiersmen of Silicon Valley is that the internet and world wide web were developed by the wrong people"

Indeed Silicon Valley became a haven for frontier mentality. Arguably the high priest of frontier thinking is Peter Thiel, a founder of PayPal, who during a 2012 interview with National Public Radio, said: "I believe we are in a world where innovation in stuff was outlawed. It was basically outlawed in the last 40 years – part of it was environmentalism, part of it was risk aversion."

There are very strong arguments against this view of environmentalism because lightbulbs, fridges, dishwashers, cars, washing machines, street lighting, LEDs in agriculture, and energy renewables are just some of many examples where 'green' legislation drove innovation and yielded devices that were both cheaper and more efficient. But what I find staggering is the selective myopia of the first part of his statement: it ignores completely the fact that in those 40 years, the internet and world wide web, which made PayPal possible, were developed, not outlawed.

The problem for the self-proclaimed keyboard- and boardroom-frontiersmen of Silicon Valley is that the internet/world wide web was developed by the wrong people: Joseph Carl Robnett Licklider ('JCR' or 'Lick') of the Pentagon's ARPA (Advanced Research Projects Agency, now DARPA) who conceived the Intergalactic Computer Network; Paul Baran of RAND Corporation who proposed a communication network with no central command point; Donald Davies of the UK National Physical Laboratory, who invented packet switching, which was first implemented between two computers by Lawrence Roberts of MIT and ARPA; Leonard Kleinrock (ARPA/UCLA) who pioneered application of queueing theory for message switching networks; Ray Tomlinson who implemented email on ARPAnet when on contract to ARPA; Bob Kahn and Vint Cerf who introduced the TCP/IP standard rules for computer networks; Jon Postel and Paul Mockapetris who developed the Domain Name System (the "phone book of the Internet") and who, like Kahn and Cerf, were funded by DARPA. The final element was the world wide web, proposed at CERN in Geneva by Sir Tim Berners-Lee and developed by him and Robert Cailliau.

These individuals all lived and worked in comfortable and civilised parts of the world – they were pioneers but did not pretend to be frontiersmen. The one thing that they all have in common, which is the thing that is so uncomfortable for modern-day frontier mentality: they were all – every one of them – funded by government money. The economist Oliver Wendell Holmes Jr. once said "Taxes are the price we pay for a civilised society". None of the real internet pioneers could claim to be frontiersmen because they were funded by the products of civilisation. And therein lies the problem. Those who exploited the work of the internet pioneers could hardly justify the pretence of working on a frontier if the pioneers who built the infrastructure that they rely on were not frontiersmen: instead they simply fail to acknowledge where the internet came from. The point is that the internet and world wide web were not developed by a commercial company – no company would have ever made the massive investment in time and money needed (Mazzucato, 2013) and so the risk was all taken by taxpayers.

This frontier mentality has now infected the US government. At this moment, brilliant scientists and technologists are being thrown out of their jobs in the name of efficiency by people with absolutely no understanding of what they could and would have enabled. This is a tragedy for them but an even bigger one for future generations of the US and the world.

I pick the PayPal example because there are two links to the space junk problem, the first is that its frontier mentality was passed on to SpaceX which is now owned by another PayPal founder. The other is a linguistic coincidence of the one-time motto of Facebook which, historically, also has a number of very close ties to PayPal.

"Move fast and break things"

Until 2014 this was the motto of Facebook, one of the many tools and platforms that the internet and world wide web made possible. To be fair to its author, Mark Zuckerberg, he was largely talking about destruction-testing your own things, or rendering things obsolete by producing something better – however it is now frequently interpreted as "move fast and break someone else's things".

Moving fast and breaking things happens to be a perfect description of the 'hypervelocity' phenomenon in space. We define hypervelocity as objects moving at more than about 3kms^{-1}. Objects in LEO typically move at up to about 10kms^{-1} and so a head-on collision of two objects moving at these speeds gives a relative velocity of v=20kms^{-1}. Nothing in our everyday experience comes close to such velocities, 20 times faster than the fastest jet fighter plane and 200 times faster than a flat-out Formula 1 Grand Prix car. To understand the consequences of hypervelocity, consider a grain of sand of mass m of 0.01gm. Hypervelocities are large, but not relativistic, and so we can apply the Newtonian equation $E=mv^2$ to find our sand grain has an energy E of 4kJ if it hits at 20kms^{-1}. By way of comparison, a bullet fired from a high velocity rifle has energy of less than 3kJ. It is not surprising that solar panels returned to Earth from space, such as that brought back from the Hubble Space Telescope by the Shuttle STS-61 HST Servicing Mission in December 1993, look like they have been used for rifle target practice. Moving from a sand grain to a piece of aluminium the size of a sugar cube (a mass of m=2.7gm) we get an energy of 100 kJ for such a velocity: greater than the most powerful hand grenade. Hence space junk the size of a sugar cube has the potential to shatter a spacecraft into thousands of new pieces of space junk.

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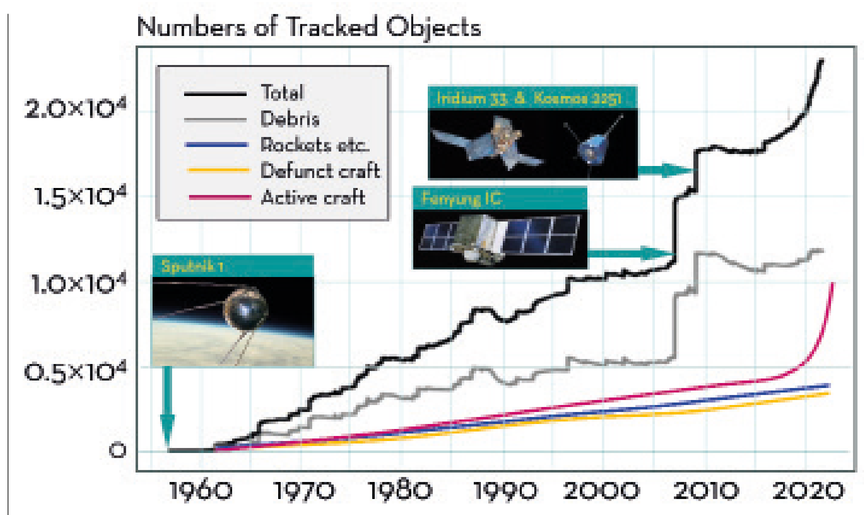
There a number of sources of space junk. There are hypervelocity collisions between spacecraft (defunct or active), between spacecraft and debris, and between debris and other debris. There are leftover rocket stages and fuel tanks to crash into. Defunct spacecraft can spontaneously explode because of leftover fluid in tanks vapourising and exerting pressure or because of deteriorating batteries. Weathering of spacecraft by space dust produces paint flecks that are tiny but potentially lethal (for example to an astronaut on an 'EVA' space walk) because of hypervelocity; similarly, vented fluids and gases from spacecraft form ice crystals that could be lethal. There are tools and other objects dropped by astronauts on EVA (rare but it has happened). There have been deliberate destructions of craft in 'Star Wars' space weapon tests. And there have been publicity stunts: very, very rare but unnecessary and irresponsible.

We categorise this junk by its size. Objects of dimensions below about 1cm are classified as 'small' and in addition to debris from collisions there is dust from rocket boosters, paint flecks, ice from nuclear reactor coolers and other fluids. It is estimated there now about 128million such objects in LEO. Medium-sized objects are 1–10cm in size. These are mainly collision debris



1 *The growth of the number of objects in Earth orbit tracked by NASA's Orbital Debris Program Office since the launch of Sputnik 1 on 4 October 1957. The lines give the total number (in black), fragmentation debris (grey); leftover objects such as rocket stages (blue), defunct spacecraft (orange). In red is the number of active spacecraft, which has grown rapidly in recent years because of commercial constellations. The two sudden increases in the debris numbers are discussed in the text.*

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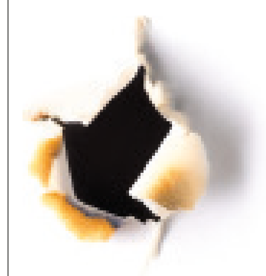


and there are estimated to be more than one million in LEO. Lastly, there are large objects of dimension greater than 10cm. These are tracked by ground-based radars and there are now 37000 of them, of which just 9100 are active spacecraft. The largest piece of junk is the defunct ENVISAT satellite which is the size of a bus and weighed 8.2 tonnes at Earth's surface. It was an Earth-observation science satellite, launched by ESA in March 2002 into a Sun-synchronous high-inclination orbit at an altitude of 773km. ENVISAT did carry enough propulsion fuel ('delta-V') to safely de-orbit but, unfortunately, during one last manoeuvre in April 2012, control was lost and the rocket motors stayed running and used up all the remaining propellant. It has been estimated that it will take 150 years to re-enter if that is left to atmospheric drag. In fact, this is almost certain to be an under-estimate because of global climate change: the heating of the troposphere by greenhouse gases gives a colder stratosphere and thermosphere above it (e.g. Shangguan *et al.* 2019). This reduces the density of upper atmospheric gases, reducing the frictional drag that is responsible for satellite orbit decay. Therefore climate change is adding to the congestion of LEO and reducing the number of satellites that can be safely launched into it (Parker *et al.* 2025). Meanwhile, ENVISAT remains of great concern as a source of more space debris as two catalogued space objects pass within about 200m of it every year.

Figure 1 shows the evolution of the numbers of known objects in space (large junk, defunct craft and active craft) since Sputnik was launched on 4 October 1957. These are trackable objects of diameters exceeding 10cm. The big rise in recent years comes from the commercialisation of space, particularly SpaceX's Starlink constellation of satellites, although the total is also pushed up by increasing debris that is rising again, having been in slight decline for a few years before 2008 because of thermospheric warming by enhanced solar activity.

There are two major step increases in debris. We happened to observe the first of the two events, which took place on 11 January 2007, in test data from the EISCAT Svalbard radar which we had recently commissioned. It turned out to be debris from a defunct Chinese meteorological satellite called Fengyung IC in orbit at an altitude of 865km that had been destroyed in a 'Star Wars' test conducted by the Chinese military. We now know this generated over 4000 pieces of trackable debris. On 22 January 2013, one such fragment (labelled Fengyung IC Deb 30670) hit and destroyed the small Russian satellite BLITS 35871. Predictions are that in 100 years' time, this debris will only have decreased by 20% (and global warming may make even that an overestimate). This test was hugely irresponsible, as well as unnecessary – demonstrating that it was much more of an international geopolitical statement than a real technological test. But that was not the first such test: for example, in September 1985, the US Air Force destroyed the Solwind P78–1 satellite (at 555km altitude) with a missile launched from an F-15 aircraft. The debris were not as numerous (the blip in the graph is considerably smaller) and it decayed away faster because of the lower altitude. But therein lies the key point about irresponsible behaviour: if you grant yourself licence to act irresponsibly you have no credibility if you complain about others who later do the same. Subsequently, India have carried out a similar test/demonstration in 2019, followed by Russia in 2021, the latter posing a real threat to the ISS.

The second sharp rise in the graph, on 10 February 2009, was an accident of a kind that is inevitable. This was a collision between two high-inclination polar orbiting LEO satellites Iridium 33 & Kosmos 2251.

So is the International Space Station at risk from collisions like this? The answer is yes. The ISS has a 'Whipple shield', which presents a series of barriers to incoming objects, each of which slows the object and disperses it into smaller pieces so that it fails to penetrate the skin of the station. The problem is that it only works for objects up to about 1cm is size and deteriorates over time with each impact. This means it is vital to monitor the orbits of larger debris pieces using ground radars and manoeuvre the ISS out of harm's ways. In the five years before 2003, six such 'dodging' manoeuvres were needed; 14 were needed in the past 5 years. The number goes up and down with the solar activity level, for reasons we will discuss below, but the trend is clear.

Space junk in different orbits

There are several places where we send spacecraft. Missions to the outer solar system can drift into interstellar space, as the Voyager craft are doing, or be burned up in the atmosphere of a gas giant, which was the end-of-life strategy for the Cassini mission. Closer to Earth are the Lagrange points, features in the gravitational field around which we can maintain craft in halo orbits with minimal fuel. The L1 point is useful for monitoring the Sun and its outputs that influence Earth; L2 gives opportunities for astronomy as one can look away from the noise sources that are the Earth and the Sun; L5 will soon be used for space weather forecasting. These orbits are not heavily used and the weakness of the gravitational feature means only a small residual delta-V is needed to put craft on to trajectories that lead them to fall into the Sun. Hence space junk is not a problem here.

Closer to Earth, it is a very different story. Its usefulness for broadcasting, communications and Earth observation make GEO – at a geocentric distance of 6.6 Earth radii – very crowded indeed and there is no easy de-orbiting strategy. Instead, craft are retired to a 'graveyard orbit' just outside GEO and it is hoped the collisions and explosions do not send debris back toward active craft. There are high-apogee MEO orbits that are used for navigation systems and, although there is again no clear de-orbiting strategy available, it is not as crowded an area of space as GEO. The biggest concern is LEO which is very crowded indeed, with the most space junk. Here the de-orbiting strategy is to burn up retired craft in the upper atmosphere. This can be left to orbital decay but may need to be actively hastened using 'clean-up' craft. However, this needs careful planning and must be carefully timed.

> *"If you grant yourself licence to act irresponsibly you have no credibility if you complain about others who later do the same"*

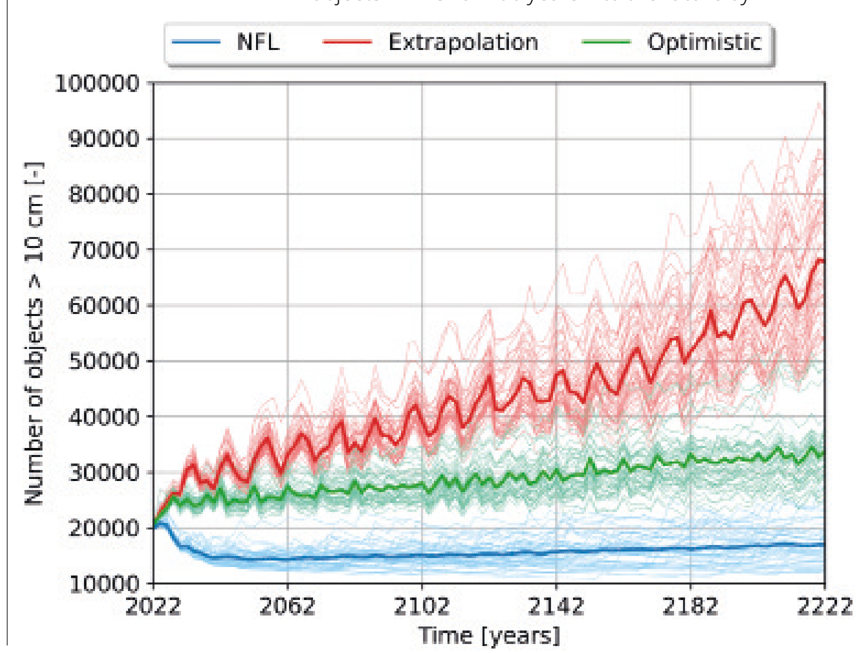
Kessler syndrome

A big concern is a theoretical prediction of runaway space junk proposed in 1978 by NASA scientists Donald Kessler and Burt Cour-Palais. In this chain of events, space junk generated when debris from one collision causes other collisions and so on until space becomes effectively unusable because the risk of collision is too high. There is no consensus as to where we are on the predicted exponential growth curve of space junk that leads to the Kessler syndrome – but there is no doubt that if we act irresponsibly and do not implement solutions, then it will become a major problem at some point in the future – and it would be a problem that we would be stuck with for a very long time. Some argue that, like many pollution problems, it will be a crisis in slow motion and unfold gradually. Several experts believe that the Iridium-Kosmos collision in 2009 was the first major incident of an unfurling Kessler syndrome. There are Monte-Carlo numerical simulations and analytic software that predict exponential growth of debris at some altitudes and more linear growth at others. A key unresolved question is how much debris rise is already 'baked in' and how much depends on future launch rates. Some simulations suggest that space junk will double over the next two centuries, even if all launches ceased today.

The models illustrate the positive feedback loops caused by collisions that could take numbers towards the onset of a Kessler syndrome, but some do not set a threshold at which this sets in. The more sophisticated models consider altitude variations and do predict Kessler syndrome onset at higher altitudes where atmospheric debris removal is slow (e.g., Hudson 2023). In particular, Adilov *et al.* (2018) show that spacecraft lifetimes at some high altitudes would become uneconomically short.

Figure 2 shows predictions of numbers of large objects in LEO for 200 years into the future by Giudici *et al.* (2024). The thin lines are individual model runs and the thick lines the variation of the mean for that ensemble. The model considers three scenarios for future space use. The blue lines are for a No Further Launches ('NFL') scenario in which no craft are launched after the modelled start date of 2022. This results in an initial 25% decrease in numbers over the next 25 years as low altitude satellites (for example Starlink) fall in altitude and burn up. However, collisions and explosions of defunct craft mean that numbers subsequently rise again.

2 *Model predictions by Giudici et al. (2024) of the number of objects in LEO of diameter greater than 10cm. The thin lines are individual runs and the thick lines are the means of the ensemble of 50 runs for each of the three launch rate and de-orbiting scenarios described in the text.*



The red lines are the 'extrapolation' scenario, which includes planned launches after 2022 and their stated post-mission disposal ('PMD') plans: it extrapolates the current behaviour in terms of both launch traffic and disposal rate. This results in the average number of objects rising by a factor of about 2.40 in 200 years, although at the 2-sigma points of the ensemble indicate that this factor could be between 1.6 and 3. Note the distinct solar cycle variation caused by upper atmospheric temperatures and densities being enhanced at sunspot maximum.

The green lines are the 'optimistic' scenario.. This is a very optimistic scenario in which End-of-Life ('EOL') capabilities are considerably improved with respect to current standards, and is used to assess the severity of the space debris problem even in the most conservative case. In this case the launch rate is as for the Extrapolation scenario but 99% of spacecraft are subject to controlled re-entry and burn up. This (highly) optimistic scenario still results in a 60% rise over the next 200 years.

Debris reaching Earth's surface

On 8 March 2024 a 0.7kg piece of space junk ripped through the home of the Otero family in Naples, Florida. It has now been identified as a support structure weighing two tonnes from a pallet of batteries that was jettisoned from the ISS in 2021 after a refurbishment. Fortunately nobody was killed, but the Otero family are now suing NASA in what many regard as a test case, with major implications about the liability of commercial companies exploiting space.

Another well-publicised case occurred on the penultimate day of 2024 when a ring of diameter 2.5m and weighing 500kg fell very close to Mukuku village, Makueni County, Kenya. Some believed it had not come from space because of the lack of charring in the images but it was red hot when first found and other pieces found nearby have been identified as space junk. The Kenyan space agency has concluded it was a separator ring from a launch rocket. Space agencies have declared they do not recognise the junk as theirs and its origin remains a mystery. Rocket parts that fell on farms in Saskatchewan, Canada and in North Carolina in 2024 have been identified as being from a SpaceX Dragon spacecraft. Meanwhile Quantas has delayed flights because of reports of re-entering space junk and flights over the Caribbean had to be diverted after the Space-X rocket explosion on 16 January 2025.

In general, space junk burns up in the atmosphere and so reports of junk reaching the ground are rare. It has been estimated that currently there are between 40 and 120 instances per year, depending on the size of the craft re-entering. In recent years, a moderate-sized object (meaning one metre or larger in dimension) re-entered Earth's atmosphere roughly once a week, while smaller objects re-enter about twice a day. However, in January 2025 alone 120 Starlink satellites re-entered; that rate, of 4 per day, is set to last as it is close to the average launch rate of 3.4 per day between 2019 and 2023. As of March 2025, SpaceX had launched a total of 8144 Starlink satellites. Of these, 1053 have either failed or deorbited, leaving 7135 satellites currently in orbit. Among these, 6492 are fully operational, while the remainder are in various stages of testing or commissioning.

> *"The 28-fold increase in the rate of de-orbiting craft means we should be prepared for a 28-fold increase in objects falling to the surface from space"*

This is a 28-fold increase in the rate of de-orbiting craft compared to five years ago. There is no obvious reason to believe that the fraction that yield debris that reaches the Earth's surface will change and so we should be prepared for a 28-fold increase in objects falling to the surface from space. The large expanses of oceans, deserts and mountains mean that only about 3% of Earth's surface is populated by humans so the risk is extremely low but the hazard posed is extremely great. The biggest concern is that a small piece of debris could bring down a passenger airliner. On 25 December 1996, a China Southern Airlines Boeing 757, en-route from Beijing to Wuhan, made an emergency landing after an impact at 31 500 feet. There was a crack in the outer pane of the three-ply windshield, almost certainly caused by a small piece of space junk. Such events have extremely low probability, but not zero. As both launch rates and flight numbers increase, so does the probability; given long enough this will happen. Reports of falling debris have already caused precautionary delays and diversions to passenger flights (Wright *et al.* 2025).

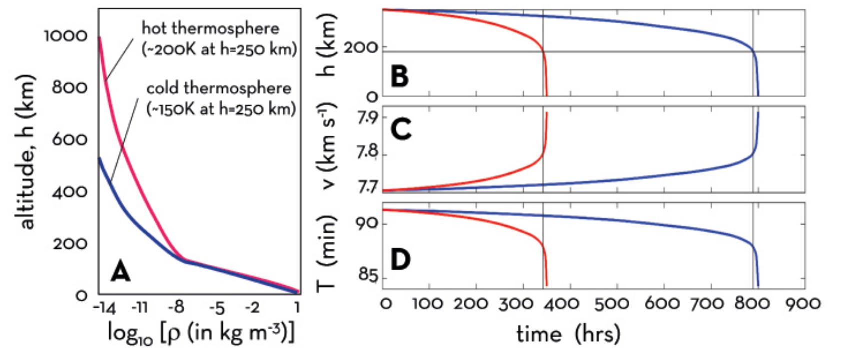
Controlled deorbiting

Space agencies are taking the problems seriously. Most are concentrating on the problems for LEO. The concept of using a net to capture large junk was successfully tested by the UK's RemoveDEBRIS satellite. ESA's ClearSpace 1 will use tentacles, and NASA are also looking at harpoon and magnet technologies. Once they have captured a defunct satellite, these 'clean-up' missions will slow it down using retro rockets causing both to drop in altitude. Re-entry becomes inevitable and imminent near 190km, at which point the clean-up satellite releases that junk and moves itself back up to find the next piece, while the junk re-enters and burns up.

On re-entry, a spacecraft begins to break up with elements such as solar panels being shed first. Then the main part of the craft then begins to rupture and finally fragment. This means there is an extended debris trail which, because of the potential of some junk to survive to the surface, we need to be a short as possible and over unpopulated areas. This is particularly true of very large objects such as ENVISAT or, when it is no longer viable, the ISS. If the craft has some delta-V left this can be used to control the re-entry to ensure this is what happens – otherwise re-entry is uncontrolled and we risk this not being the case. At this point, space weather becomes a vital factor.

Large geomagnetic storms take place when coronal mass ejections (CMEs) from the solar atmosphere impact upon Earth' s magnetosphere, the region of near-Earth space dominated by Earth's magnetic field. How much energy is extracted by the magnetosphere depends upon the strength and, crucially, orientation of the magnetic field in and ahead of the CME. A sizeable fraction of that energy is deposited in the upper atmosphere at high latitudes by auroral particle precipitation and by currents that flow in the ionosphere. This heating spreads around the globe causing an upwelling of the upper atmosphere and so increasing the frictional drag on all objects in LEO. This is why the orbits change so much more at solar maximum, when CMEs are much more frequent. It is also why SKYLAB was brought down earlier than expected when the 11-year solar activity cycle was of greater amplitude than expected.

The red and blue lines on the left-hand plot (A) of figure 3 show the mass density altitude profiles (ρ as a function of h) of the upper atmosphere, the 'thermosphere', for high and low temperatures, respectively. The right-hand plots shows the orbital characteristics (B, altitude, *h*; C, speed, *v*; and D, orbital period *T*) of a typical re-entering spacecraft for these atmospheric profiles. The horizonal black line in B is considered to be the re-entry altitude of 190km, below which orbiting is no longer possible. The key point is how much sooner re-entry occurs if the atmosphere is heated. The difference is almost 500 hours, roughly 300 orbits. Consider a Sun-synchronous, high-inclination orbit like that of ENVISAT, for which the geographic longitude of the orbit path changes by about 22.5° from one orbit to the next: this means that, depending on the thermospheric heating, the debris trail could be anywhere on the planet!



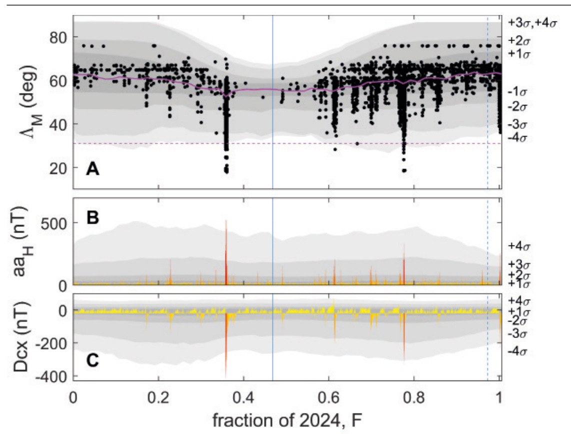
3 *An illustration of the effects of upper atmospheric temperature on satellite de-orbiting. The red and blue lines are for a hot and a cold thermosphere. A shows model thermospheric altitude profiles of mass density, r. The evolution of the altitude, h, orbital speed, v, and orbital period, T are shown in B, C and D, respectively, for a model spacecraft of average size and effective drag coefficient. The horizonal black line in B is the re-entry altitude of 190km.* (after Knipp et al. 2005)

The importance of space weather

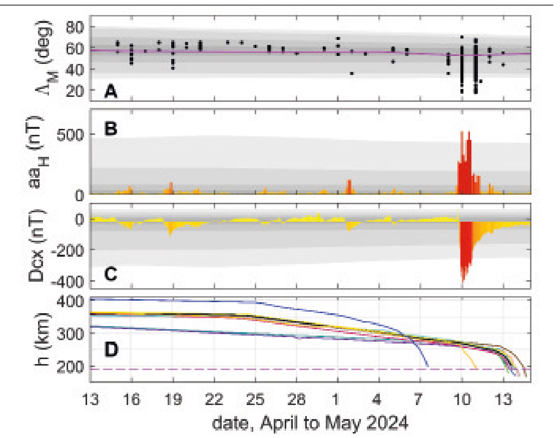
If we are to safely de-orbit these very large pieces of junk we need to know the state of the global thermosphere and avoid times when it may change suddenly. This calls for accurate and reliable space weather forecasts so we do not attempt to de-orbit large junk at a time when a large CME may impact Earth and bring the junk down early. After a relatively quiet solar cycle, 2024 was a year in which there were exceptionally large space weather events. Figure 4 shows the four events in which the low-latitude extent of the aurora reached 4*σ* levels and these were accompanied by geomagnetic storms seen in both mid-latitude geomagnetic indices (dominated by auroral substorms) and low-latitude geomagnetic indices (dominated by the magnetospheric ring current) that reached the 3*σ* or 4*σ* level. The largest was the event of 10/11 May 2024, which is shown in more detail in figure 5.

The lowest panel of figure 5 shows the altitude of 12 Starlink satellites that fell out of orbit because of the space weather (Ashruf *et al.* 2025). Eleven of them were finally pushed out of orbit by the geomagnetic storm, but all were declining in altitude before then and indeed one satellite (Starlink 57649 – the blue trace) actually fell out of orbit before the storm. The sequence of solar events that led to the May 2024 storm has been recorded by Hayakawa *et al.* (2025). Ashruf *et al.* (2025),attribute the decline in satellite altitudes before the storm to enhanced heating of the thermosphere by solar EUV emissions before and during the CME releases.

There was a new and worrying feature of the May storm in relation to space junk: Parker and Linares (2024) show that between 11 and 13 May there were an unprecedented number of autonomous spacecraft manoeuvres (peaking at nearly 5000 in a three-hour window compared to about 300 before the event). These were largely Starlink craft that had avoided re-entry by moving to a greater altitude. The problem is that the remainder of the craft operating in LEO, and all the space junk, will have fallen in altitude, objects with larger frictional drag falling more than smaller ones. Starlink satellites do not yet have fully autonomous collision avoidance mechanisms in that they act using data on nearby orbiting craft and junk recorded by ground-based radars and telemetered up



4 *Auroral and geomagnetic activity in 2024. The black dots in panel A show daily values of the quasi-dipole geomagnetic latitudes, L_M, of observations of aurora in the northern hemisphere. The light to dark grey areas are delimited by, respectively, the ±4s, ±3s, ±2s and ±1s points, where s is the standard deviation, of the distributions (for that fraction of a calendar year, F) from 220 000 recorded auroral observations between 1650 and 2025 (Lockwood et al. 2025): the mauve line shows the variation in the means of the distributions. Panel B shows the mid-latitude aa_H geomagnetic index (Lockwood et al. 2018a;b), the grey bands again showing the 4s, 3s, 2s and 1s points of the distributions from the 458 754 three-hourly observations available for 1868–2025. The corresponding plot for the low-latitude Dcx geomagnetic index (Karinen and Mursula 2005) is shown in panel C. The Dcx index is available for 1932–2024 and there are 814 238 hourly samples.*



5 *The loss of 12 Starlink satellites caused by the geomagnetic storm of 10/11 May 2024. Parts A, B and C are details of fig. 4 for the week of the storm and the three weeks preceding it. Panel D shows the variations in the altitude, h, of 12 Starlink satellites which re-entered (orbital data from Ashruf et al. 2025). The re-entry altitude of h = 190km is shown by the mauve dashed line. Note that satellite 57649 (in blue) re-entered before the geomagnetic storm and all satellites showed some orbit degradation prior to the geomagnetic storm.*

to the satellites. In a space weather event such as that in May 2024, orbits are changing fast and unpredictably and so the collision risk is greatly enhanced by having some manoeuvring craft and others including junk (tracked and untracked) that are not.

Another example of how one can be caught out by a space weather event was the unexceptional space-weather storm on 7 February 2022 (Lockwood *et al.* 2023) which caused the loss of 38 out of 49 recently-launched Starlink satellites. It should be said here this happened because of a good and responsible launch policy adopted by SpaceX. The lost craft were at a vulnerable low orbit at just 210km altitude, where they undergo tests: at this altitude, those that fail the launch tests can be readily de-orbited. Only after passing the tests do the craft use their autonomous delta-V to move up to their operating altitude from where de-orbiting would take much longer. Unfortunately this loss caused SpaceX to raise the altitude of initial orbit, reducing the ability of the company to reduce space junk arising from craft that have failed.

The chief executive officer and chief engineer at SpaceX, Elon Musk, has in the past made laudable donations to enhance the training of young scientists and engineers, but recently has greatly undermined these, making technological R&D and science a much less attractive career path by his role in sacking existing scientists and engineers working for the government. In addition, Starlink satellites are doing real damage to this aim: astronomy is key in technological societies because it sparks interest in physics, mathematics and engineering, and undoubtedly has been the inspirations for a great many careers in all areas of science and technology. This invariably begins with ground-based observations. Already these are seriously compromised by light pollution (e.g., Mróz *et al.* 2022) and major new radio telescopes like the Square Kilometre Array and LOFAR are subject to noise from Starlink satellite emissions (Di Vruno *et al.* 2023). To give SpaceX due credit, they have responded by trying to reduce the problems with some, but limited, success. So far, SpaceX has launched 8000 Starlink satellites. It has received approval from the Federal Communications Commission (FCC) to deploy up to 12000 satellites in its Starlink constellation and the company has filed applications for a further 18 000 satellites. There are serious concerns that this is neither sustainable nor responsible.

And just when you thought we were fixing that hole...

There is another hazard behind the issue of space junk that is a humanitarian issue. It is much more insidious and ubiquitous but we do not yet have enough understanding of it. Ironically, our solutions to the LEO space junk problem will directly add to this problem.

Aircraft observations of the stratosphere, at altitudes around 25km, are now revealing alarming rises in pollution by metals such as aluminium, lithium, iron, and titanium oxides. The elemental abundances of this pollution leave no doubt that it is coming from the burning up of de-orbiting spacecraft and space junk (Murphy *et al.* 2023). The more craft that we put in LEO, the worse this will get. At the rate of planned commercial launches, these metals are a very real threat to atmospheric ozone (Ferreira *et al.* 2024) and it is thought that the recovery of the Antarctic ozone hole made possible by the Montreal protocol banning chlorofluorocarbons (CFCs) may already have been slowed by de-orbiting space junk. This time the effect will be global. The ozone hole over Antarctica is driven by CFCs accumulating in the stratosphere and being broken down by UV light, releasing chlorine radicals which lead to the catalytic destruction of ozone: the effect is strongest over the South Pole because the southern polar vortex trapped the CFCs for long enough to break down ozone. In the case of ozone destruction by metals, the prolonged effect of solar UV is not required and so the effect will be global.

"It is thought that the recovery of the Antarctic ozone hole made possible by banning chlorofluorocarbons may have been slowed by de-orbiting space junk, and this time the effect will be global"

The Antarctic ozone hole gave rise to one of the greatest and most important speeches ever given by a British Prime Minister and, in my view, the best scientific speech ever given by any world leader. It was given by Margaret Thatcher at the United Nations General Assembly in New York on 8 November 1989. Thatcher was Britain's first ever female Prime Minister, but she was much less proud of that than she was about being Britain's only scientist PM. Her speech was clear, emphatic and extremely accurate scientifically (true then and still true today). It contains a massively important statement that her latter day free-market admirers choose to overlook: "We should always remember that free markets are a means to an end. They would defeat their object if by their output they did more damage to the quality of life through pollution than the well-being they achieve by the production of goods and services".

We urgently need to remember the caveats of Thatcher and Frederick Jackson Turner, stop the frontier mentality about near-Earth space and consider instead its sustainability as a hugely valuable resource. I will end with another quote, this one from one of the wisest and prophetic observers of both science and humanity that the world has ever known. Carl Sagan in his famous 'Pale blue dot' speech (recorded in his 1994 audiobook) echoed Fred Hoyle's great predictive insight "Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves … To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we've ever known." ●

AUTHOR

Prof Mike Lockwood, University of Reading, UK, is the President of the RAS 2024–26.

REFERENCES

Adilov N ***et al.*** 2018) *Economics Letters* **166** 79
Ashruf A M ***et al.*** 2025 *arXiv,* **2410.16254v1**
Di Vruno F ***et al.*** 2023 *Astron. & Astrophys* **676** A75
Ferreira J P ***et al.*** 2024 *Geophys. Res. Letts* **51** e2024GL109280
Giudici L ***et al.*** 2024 *Acta Astronautica* **219** 115
Hudson J 2023 *J.Student Res.***12(1)**
Hayakawa H ***et al.*** 2025 *Astrophys. J.* **979(1)** 49
Karinen A & Mursula K 2005 *Ann. Geophys.* **23** 475
Kessler D J & B G Cour-Palais 1978 *J. Geophys. Res.* **83(A6)** 2637
Keskitalo E C H 2024 *Frontier Thinking and Human-Nature Relations: We Were Never Western.* Routledge, London.
Knipp D J ***et al.*** 2005 *The Physics Teacher* **43(7)** 452
Limerick P N 1987 *The Legacy of Conquest: The Unbroken Past of the American West*. W W Norton & Company, New York
Lockwood M. ***et al.*** 2018a *J. Space Weather Space Clim.* **8** A53
Lockwood M ***et al.*** 2018b *J. Space Weather Space Clim.* **8**
Lockwood M ***et al.*** 2023 *J. Geophys. Res. Space Phys.* **128** e2022JA031177
Lockwood M ***et al.*** 2025 *Mon. Not. Roy. Astron. Soc.* in press.
Mazzucato M 2013 *The Entrepreneurial State: Debunking Public vs. Private Sector Myths.* Anthem Press, London.
Mróz P ***et al.*** 2022 *Astrophys. J. Letts* **924** L30
Murphy D M ***et al.*** 2023 *Proc. Nat. Acad. Sci.* doi:10.1073/pnas.2313374120
Parker W E & Linares R 2024 *J. Spacecraft Rockets* **61(5)** 1412
Parker W E ***et al.*** *Greenhouse gases reduce the satellite carrying capacity of low Earth orbit.* Nat. Sustain (2025). doi.org/10.1038/s41893-025-01512-0
Shangguan M ***et al.*** 2019 *Atmospheric Chem. Phys.* **19(10),** 6659-6679
Turner F J 1890 *The Frontier in American History*. Henry Holt, New York.
Wright E ***et al.*** 2025 *Scientific Reports* **15(1)** 2966
Worster D 1979 *Dust Bowl: The Southern Plains in the 1930s.* Oxford University Press