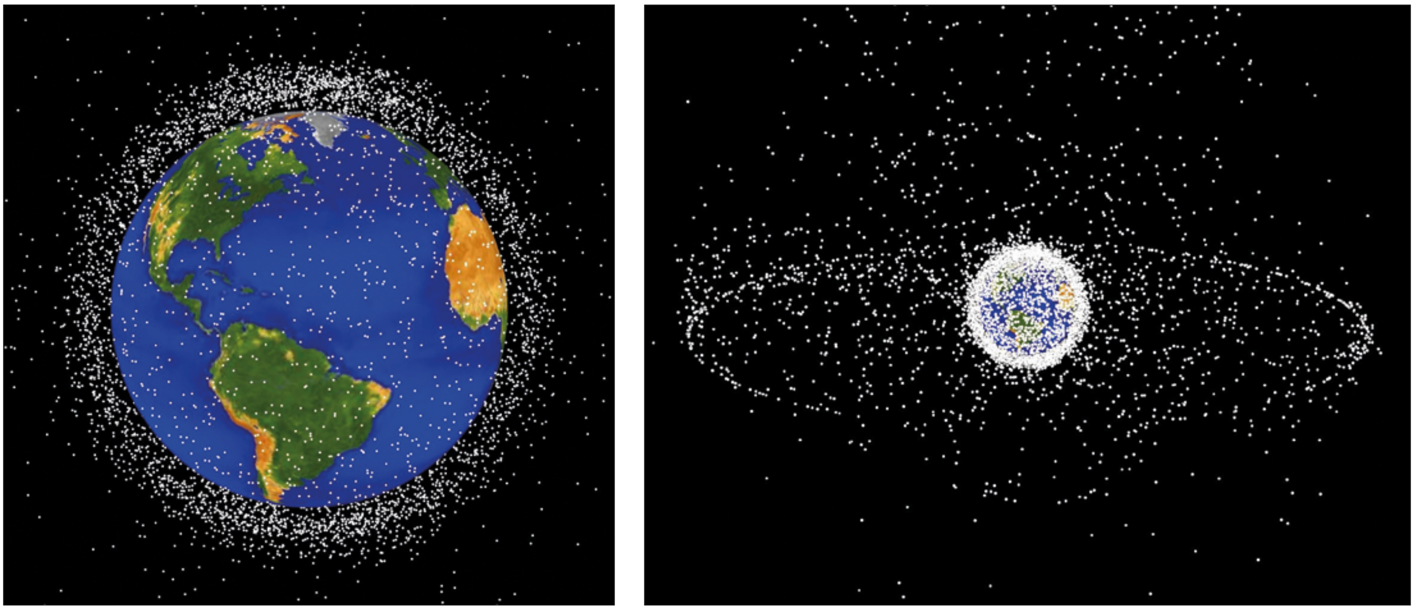


1 Illustrations of the number of objects in low Earth (left) and geostationary orbit (right) that are currently being tracked. (NASA Orbital Debris Program Office)

Space dust and debris near the Earth

Penny J Wozniakiewicz and **Mark J Burchell** survey the dust environment around our planet, now and in the future, as discussed at an RAS Specialist Discussion Meeting.

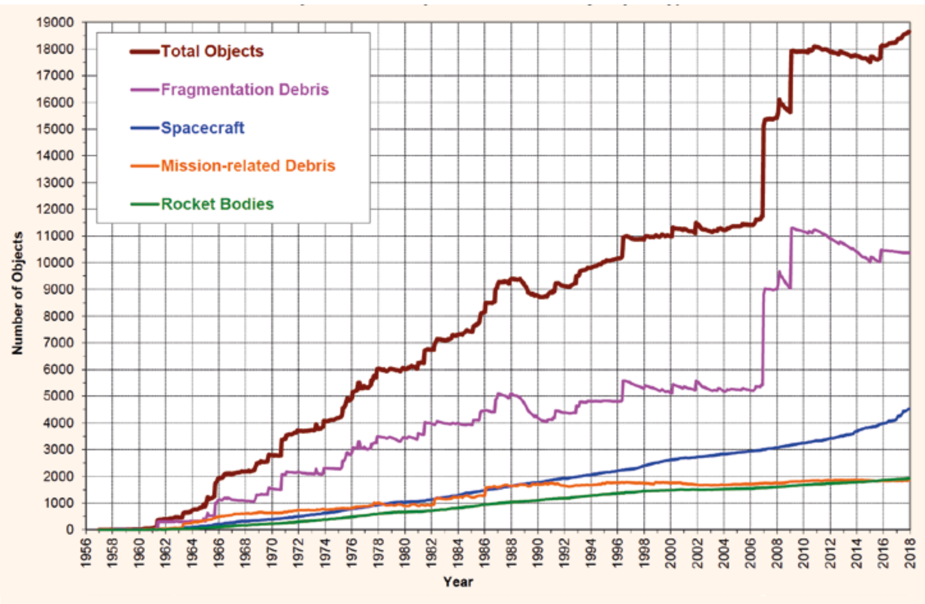
In November 2018, the RAS held a one-day meeting on the subject of dust near the Earth. Just over 50 people attended to hear speakers including representatives of both NASA and ESA, with additional contributions from the UK Space Agency (UKSA), international universities and the industrial sector – evidence of the wide-ranging significance of this topic. The growing amount of dust generated by humanity's activities in space is a major concern. Spent rocket upper stages, dead satellites and material from damaged spacecraft all contribute to this growing hazard, which, if left unchecked, will eventually pose a threat to future activities in space. Equally, the meeting addressed natural, cosmic dust, its origins and questions of current interest. The meeting also discussed new technologies to measure space dust, in terms of both its flux and its composition (particularly important to distinguish its origin as natural or arising from our space activities). The meeting contained a plea to monitor dust in cis-lunar space starting now, because as human activity increases in the region of the Moon, moving significantly beyond low, medium and geostationary orbits of the Earth, we will take our debris with us.

The UK and the whole space community has long had an interest in cosmic dust. Some of the earliest scientific instruments flown on spacecraft were designed to measure such dust and the hazard it might pose to space vehicles as a result of the high relative speeds on impact (many km s^{-1}). Indeed, it was soon realized that spacecraft themselves generate space debris as by-products of their day-to-day operation, products of degradation of their components in the harsh environment of space or even the result of catastrophic events. It is therefore inevitable that as our activities in space increase, the population of such matter will grow too (figures 1 and 2). Most of our space vehicles are in low, medium and geostationary Earth orbits (LEO, MEO and GEO respectively), exacerbating the risk there. The November meeting devoted to the topic of dust near the Earth followed a meeting in December 2015 (Wozniakiewicz 2017), which looked at cosmic dust more broadly. The current meeting focused on dust detected near the Earth, as this is where the human contribution to the dust population is growing – and worrying.

> "It is no surprise that both NASA and ESA have offices devoted to space debris"

Space debris offices

Given the importance of securing long-term, safe access to space, it is no surprise that both NASA and ESA have offices devoted to the subject of space debris. The first speaker at the meeting was **Jer-Chyi Liou** (NASA Orbital Debris Program Office, https://orbitaldebris.jsc.nasa.gov). Liou, who is NASA's chief scientist for orbital debris, focused his talk on the origin and nature of orbital debris. A simple definition of such material is any human-made object (or fragment thereof) in space which no longer serves a useful function. Orbital debris can range in size from, for example, 10 µm diameter Al_2O_3 spheres added to solid propellants in rocket boosters and which are not all burnt during combustion but emerge in the rocket exhaust, to metre-sized spent upper stages of rockets or old, disused satellites. Then there are debris fragments, which can be anything from paint flakes, or the fragments of a spacecraft after it was disrupted (partially or fully) either by an internal explosion or an external cause.



2 Summary of all objects in Earth orbit officially catalogued by the US Space Surveillance Network as of 2018. "Fragmentation debris" refers to objects resulting from the break-up of satellites, while "mission-related debris" are by-products of the planned mission. Sharp increases in abundance of fragmentation debris can be seen in 2007 and 2009 related to the Fengyun 1C and Iridium–Cosmos events respectively. (*NASA Orbital Debris Quarterly News* February 2018, vol. 22, issue 1)

Old spacecraft can explode in isolation as a result of faulty batteries, for example, or spare propellant left unvented in tanks on board. Or damage can be done by the impact of foreign bodies. Impactors can be natural dust grains, fragments of other spacecraft, or indeed whole other spacecraft due to accidental or deliberate collisions.

Liou cited examples of spacecraft collisions: in 2009, there was an accidental collision between Cosmos 2251 and Iridium 33; in 2007, a missile deliberately targeted and destroyed the Chinese craft Fengyun 1C during a weapons test. Both these events generated huge quantities of debris, shown in figure 2. Liou pointed out that there are now more than 18 000 large (metre scale) objects of human origin in Earth orbit. Of these, 1700 are operational objects and around 1000 are old rocket stages, with another 1000 pieces of operational debris. But the largest single category of large objects is the more than 10 000 pieces of fragmentation debris, showing how the break-up of spacecraft drastically increases the hazard at large size ranges. At smaller sizes, there are around 500 000 objects at the 1 cm scale, and some 100 000 000 at the millimetre scale. While 1 mm does not sound a worrying size, the high relative speed when it impacts another body in Earth orbit (mean speed 11 km s^{-1}) means it can punch through steel plate causing not only interior damage, but also generating more debris fragments in the process, risking a cascade effect. An example of this multiplying effect was an impact on the European Space Agency's Sentinel-1a satellite in 2016, which produced some loss of power for the satellite, but also generated six trackable (greater than ~10 cm) pieces of new debris. There is an estimated 7600 tonnes of material in space near the Earth; this is constantly increasing at a linear rate with no sign of a slow-down. Although fragmentation products dominate numerically, in terms of mass most of the material lies in spacecraft and rocket bodies. In terms of spatial density, the largest concentrations are found in LEO (up to 1000 km altitude), with spikes in MEO (around 20 000 km, where many global navigation systems are found) and GEO (36 000 km, where geostationary satellites are positioned).

"While 1 mm does not sound a worrying size, it can punch through steel plate"

In the mid-1950s, before the space era, there was no such material in space.

Liou explained that NASA has long realized the impact risk posed by orbital debris or natural dust. For example, the space shuttle (STS) was subject to an evaluation of impact risk in the 1990s, and additional protection was installed at key vulnerable areas, such as the radiators on the interior of the cargo bay doors, which were routinely exposed to space during flight to help cool the craft. In 1997, extra 0.5 mm thick aluminium shielding was placed over the coolant pipes, along with valves to isolate any leaking pipes from the rest of the freon coolant circulating system. The value of such measures was shown in 2009, when post-flight analysis found an impact feature directly above a coolant pipe. Without the extra shielding the coolant pipe would have been penetrated, and that mission (STS-128) aborted within 24 hours.

Not surprisingly, NASA runs a full suite of activities relating to impact hazard assessment in Earth orbit. This includes monitoring the environment for larger (decimetre scale) objects via radar and optical telescopes, and providing flux modelling tools (combined with impact damage modelling) to spacecraft designers and mission planners. NASA also organizes laboratory tests to look at fragmentation of spacecraft, such as the DebriSat experiment in 2014 (see Polk *et al.* 2015 or https://orbitaldebris.jsc.nasa.gov/measurements/debrisat.html), in which a full-sized satellite mock-up was impacted in the laboratory by a 570 g projectile at just under 7 km s^{-1}. The vast number of resulting fragments are being carefully characterized by researchers to provide a better understanding of fragmentation processes. NASA is also developing a new generation of real-time dust-flux monitors to deploy in Earth orbit. This resulted in the launch in December 2017 of the real-time electronic DRAGONS detector (a NASA, USNA, US NRL, Virginia Tech. and University of Kent collaboration, see https://www.nasa.gov/mission_pages/station/research/experiments/2145.html) placed on the outside of the International Space Station (ISS). Although this was only operational for just under a month (before a comms error ended its lifetime unexpectedly), data on several impacts were sent back to Earth and are currently being analysed.

Living with space dust

The second speaker was **Tim Flohrer** (ESA Space Debris Office), who discussed living with space dust – reflecting the acceptance that not only is the natural micrometeoroid population always going to be present, but that from now there is also the human-generated contribution. Like NASA, ESA offers support to those designing spacecraft so that they can model the probable dust flux and the consequences of an impact (with the MASTER model, as compared to NASA's ORDEM model). Again like NASA, ESA places an emphasis on mitigating the flux in the first place. As an indicator of impact consequences, Flohrer pointed out that impact from a centimetre-scale object can lead to full mission loss on most craft and is at the limit of the shielding capabilities on the ISS – yet there are around half a million centimetre-sized objects in Earth orbit. The 2016 impact on the solar panel of Sentinel-1A was probably from a 1 cm sized object, and left a 40 cm feature on the solar panel it struck (figure 3). ESA estimates there have been more than 490 spacecraft break-up events of all types since 1960. Five arose from collisions with other vehicles (deliberate or otherwise), and another 11 came from known small particle impacts. The largest single cause of break-up lies in the propulsion systems (141 events), with another 105 of unknown origin. There does appear to be a decline in propulsion-related break-ups recently, however, as a result of fewer launches and better passivation techniques.

Before anybody panics, however, Flohrer turned the flux numbers into timescales. Given that the flux varies with altitude, the risk depends on where your spacecraft orbits (see table 1). It also, of course, depends on how big your spacecraft is. The risk is increasing with time as the debris population increases, but with monitoring efforts using radar, the orbits of larger particles can be calculated and collision avoidance manoeuvres can be performed to help reduce the risk of impact. Earth orbit is still usable, but we need to keep it that way.

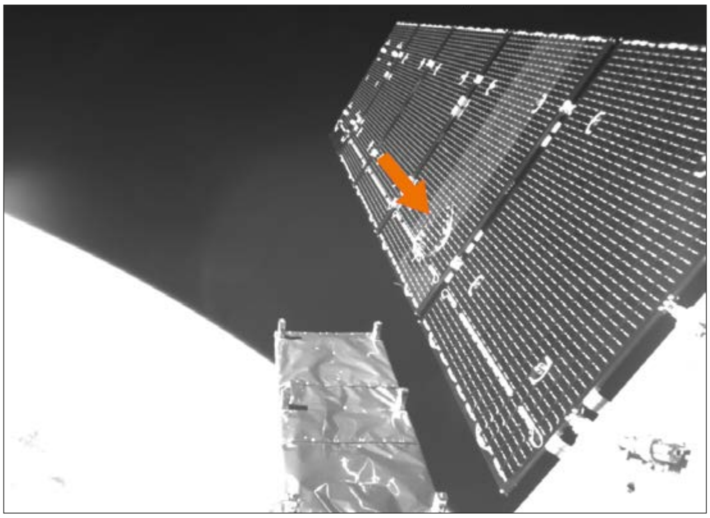
Flohrer also reminded the audience that not all objects stay in space; there are natural mechanisms that reduce populations. Solar radiation pressure moves objects around the solar system, and aerodrag from the Earth's atmosphere is particularly effective for removing small objects at low altitude. Even at an altitude of 800 km, a typical satellite will only last 50 years in space, and a 1 mm object just two years or so. While this helps remove material from LEO, it also involves uncontrolled entry into the atmosphere. Such events are evenly distributed at all longitudes, but favour equatorial latitudes. While small dust will burn up on entry, larger spacecraft fragments can reach the Earth's surface. But the risk of injury to humans is low; the chance of death by impact from uncontrolled re-entry of space junk is one millionth of that from air travel, for example.

To help manage risks to space vehicles from impact hazards, ESA offers a suite of programmes (DRAMA) as well as the flux modeller MASTER. The full suite allows a user to consider not only the risks of an impact but, for example, allows calculation of mitigation measures to reduce uncontrolled re-entry. MASTER itself is updated regularly, featuring more sources of debris, along with the improved estimates of natural micrometeoroids. Like NASA, ESA has also flown detectors to measure dust and debris *in situ* in space and operates ground-based telescopes to monitor populations remotely. Indeed, space situational awareness is a growing part of ESA's activities, and developing a Europe-wide capability is a major task. One way that ESA is already tackling this is by providing mission planners with guidelines, such as: no object should stay in LEO for over 25 years; in GEO at end of life a shift to graveyard orbits should be routine; propulsion should limit the production of slag or additives such as Al_2O_3 spheres. When asked, Flohrer replied that the large commercial operators were keen on such measures and welcomed clarity and advice; this was one area where regulation was welcome because the benefits were obvious. However, it was not clear if all governments felt bound by the same pressures, or what new minor operators would do with low-cost objects such as Cubesats.

1 Impact frequencies at different altitudes

altitude	>0.1 mm	>1 mm	>1 cm	>10 cm
400 km	0.92 (2.2) days	7.9 (40) years	1700 years	21 600 years
800 km	0.17 (0.19) days	2.6 (3.4) years	101 years	1510 years
geostationary	1.8 (23) days	12 (660) years	71 000 years	1 020 000 years

Time for an impact of a given sized object of any origin on a spacecraft with 30 m^2 surface area at a given altitude in Earth orbit. For sizes up to 1 mm, the values given in parentheses are for impacts by debris only. (Source T Flohrer, ESA by private communication; values generated by V Braun from Master 8, 2016 analysis epoch, LEO inclination 98.7°)



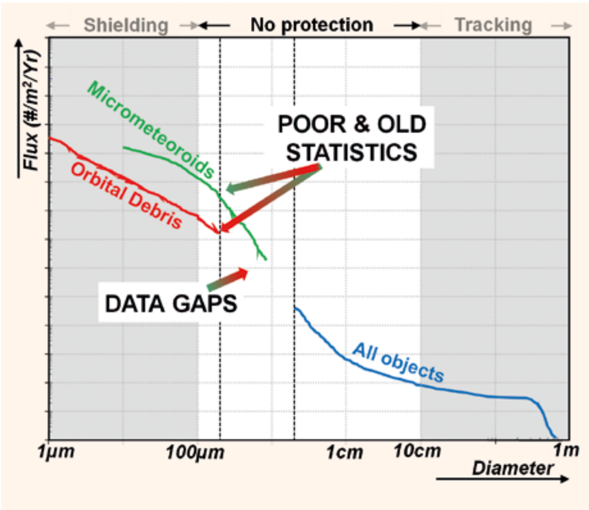
3 Sentinel-1A's solar array after the impact of a particle. The damaged area (highlighted by an arrow) has a diameter of about 40 cm. (ESA)

UK Space Agency

Toby Harris, head of orbital systems for the UK Space Agency (UKSA), then spoke about the agency's role. UKSA coordinates the UK's role in international bodies such as the IADC and UNCOPOUS, which coordinate space debris issues worldwide. UKSA is also the national regulatory body. Of current concern for it is the large satellite constellations planned to deliver broadband signals. If these are in LEO (where the latency time on signals is low) then global coverage demands large numbers, increasing the risk of close encounters and impact collisions. Helping designers understand the need to protect both their own spacecraft and the general environment is a priority. To this end, UKSA supports modelling of collisional processes in LEO that can lead to runaway growth of debris (the so-called Kessler syndrome, e.g. Kessler 2010). The intention is to support informed decision making by designers.

Simon George (Defence Science and Technology Laboratory, Dstl) spoke next. He pointed out that the UK government is encouraging growth in the UK space sector, and that improved space situational awareness is crucial to maintaining access to space. Dstl has an interest in new sensor types capable of improving the monitoring of space from the ground and characterizing on-orbit objects, and in integrating these into better data processing systems for use in space operational centres. Improved algorithms are just as important as more capable sensors.

Mark Burchell (University of Kent) then spoke of the need to extend dust awareness beyond GEO. The region around the Earth beyond GEO and out to the Moon is known as cis-lunar space. While currently dominated by natural micrometeoroids, increased human activity in this region over the next few decades will inevitably introduce debris. The nature of this debris may differ from that in LEO or



4 The measured dust flux in low Earth orbit. Radar data enable measurement of populations larger than a few mm ("all objects" line in blue). Returned surface analyses of Hubble Space Telescope surfaces enable separation of orbital debris and micrometeoroid populations for smaller particles (red and green lines). This figure is modified from that published in the US National Academy of Sciences report of 2011 (National Research Council 2011) by plotting the raw data, as reported in summaries by Kearsley *et al.* (2005, 2017) and Moussi *et al.* (2005).

GEO, if there is lunar mining, for example. Also, the duration of this debris in this orbit will be very different from that in LEO. Although there have been some dust measurements near the Moon, this is the last chance to get a ground truth for background levels of naturally occurring dust flux in cis-lunar space, before humanity more fully inhabits that region for exploration or industry. Therefore a topical working team backed by ESA is being put together to meet in 2019. This will develop the rationale for monitoring dust in cis-lunar space more fully, and propose a model suite of dust detectors for the proposed multination Deep Space Gateway project to place a habitation module in cis-lunar space in the next decade.

Anton Kearsley (retired from the Natural History Museum, but with active links to the University of Kent) spoke about how one could use spacecraft surfaces to collect dust. This effectively uses the spacecraft itself as a collector of dust (micrometeoroid or debris). The high speed of their impacts is problematic, because they disrupt, melt or even vaporize portions of the impactor. Nevertheless, remains of the impactor can be found in the impact crater which, if returned to Earth, can be analysed to reveal characteristics of the original impactor (e.g. size, structure, density, composition). Over the years, several recovery missions have used this technique to collect dust in space and return it to the Earth. In recent years, the Stardust mission to comet Wild 2 (Brownlee *et al*. 2006) was a high-profile example of collection at speed combined with Earth return. There have also been missions in LEO, such as the LDEF mission in the 1980s, and EuReCa and the Japanese SFU in the 1990s, along with several Hubble solar panel replacement flights by the STS. Examining the composition of the captured impactors can often be difficult because of the nature of the impacted surface; not all are high-purity metals free of inclusions and contaminants. Solar panels, for example, are multi-layered materials of complex construction. One solution is to design a purpose-built detector for retrieval, with substrates chosen to allow ready recognition of different impactor types.

This proposal by Kearsley led naturally to the next talk which should have been given by Penny Wozniakiewicz (University of Kent and main organizer of the meeting). However, she was unable to attend due to the slightly early arrival of her baby, so the talk was given by Kearsley. He described a proposed new dust detector for deployment in space and subsequent return for analysis – the Orbital Dust Impact Experiment (ODIE). The talk highlighted that *in situ* measurements of dust and debris are vital to fill a data gap that exists in our knowledge of dust populations at the critical millimetre scale (see figure 4). Smaller sizes have sufficient flux data provided by space-based detectors, and larger sizes can be detected by ground-based systems; there is a relatively under-explored gap in the middle. Given also that the data that exists for smaller sizes is based on surfaces exposed decades ago (and prior to big debris-generating events such as the Iridium–Cosmos and Fengyun 1C events), up-to-date measurements are also vital to ensure that existing population models and impact probabilities are correct. Having such data, combined with the ability to separate data for natural micrometeoroid and debris populations, is the goal of this mission.

"ODIE is a multilayer, passive foil collector, to be exposed in space and returned to Earth"

ODIE would be a multilayer, passive foil collector, which would be exposed in space on the exterior of a suitable spacecraft, then returned to Earth. The collection area can be scaled up depending on how many units are deployed, and the combination of surface area and exposure time will determine the sensitivity to the impactor size. The detector effectively acts as a bumper shield, disrupting impactors at the face layer and spraying material over subsequent layers depending on how far it penetrates. Detailed metallic and mineralogical compositional analysis can then be done on Earth after its return. If the pointing history of the spacecraft was stable and known, ODIE will also indicate dust trajectories. Initial laboratory testing has already been carried out, and proposals for funding for construction of full prototypes and a flight version are under way.

Asteroid dust telescope

The morning ended with a talk by **Ralf Srama** (Stuttgart University), who described the DESTINY+ dust telescope proposed for a potential Japanese mission to asteroid 3200 Phaeton (the parent body of the annual Geminid dust shower). To be launched in 2022, the mission involves multiple Earth fly-bys over two years, followed by a lunar fly-by and then a cruise phase lasting two more years before it passes 3200 Phaeton at high speed ($33\,\mathrm{km\,s^{-1}}$). As well as observing the dust near 3200 Phaeton, science can also be carried out beforehand and can involve looking for both interplanetary and interstellar dust. The DESTINY+ instrument is based on impact ionization, whereby small (sub-micron) dust grains impact a pure metal target with speeds above a few $\mathrm{km\,s^{-1}}$, producing ions that are then accelerated electrostatically and collected in a time-of-flight system to produce a mass spectrum (assuming single ionization). DESTINY+ would have a pair of drum-shaped collectors mounted side by side, looking like a giant old-fashioned pair of binoculars. The benefit of two collectors is that one can operate to detect cations, the other anions. A wide range of science goals can thus be reached, separating mineral from organic particles as well as determining fluxes.

During the lunch break, posters were displayed in the RAS Library. As well as examples of various dust-capture technologies, such as use of foams (by **James New**, University California Berkeley and University of Kent), there were dramatic images of impact features on surfaces retrieved from space shown by Kearsley. Some of these impact crater images were in 3D and show the depth of detail that can be obtained.

The afternoon session started with **Tony McDonnell** (Unispace Kent) talking about the dust environment at 1 au. McDonnell has studied cosmic dust since the 1960s, with many achievements to his name during his career as a faculty member at Kent and then the Open University. Among these was flying a dust-capture cell on the third space shuttle flight (STS-3), which on analysis after return showed four hypervelocity impacts by particles estimated to be 2–10 µm across (McDonnell *et al*. 1985).

He also talked about how various data sets had been used in the 1970s and 1980s to piece together what is now known as the Grün model of micrometeoroid flux at 1 au (Grün *et al.* 1985), which is based on various types of impactors. McDonnell and colleagues at the Open University have recently been working on a model based on sources rather than populations, the key components being a quasi-static bound interplanetary flux, an efflux of dust on hyperbolic orbits and interstellar dust. This model makes predictions over masses from 10^{-22} to 10^{14} kg! At the upper mass range, data comes not only from giant impact cratering events on the Earth, but also from the recent pass through the solar system of the object 'Oumuamaua (1I/2017 U1). He has also used previously unanalysed (and previously presumed lost) dust data from the early Pioneer 8 and 9 missions in the 1960s, to improve the Grün model and separate bound interplanetary dust from outward-flowing dust.

Samuel Diserens (University of Southampton) then described how, for his PhD work, he has been comparing NASA models of fragmentation (Johnson *et al.* 2001) arising from internal explosions vs collisions. These models are important inputs for modelling the debris environment. He compared the model results to data from four real events of break-up in explosions of rocket bodies, three examples of payload explosions and three events of break-up from collisions. He reported that the traditional NASA model worked well for the break-up of large rocket bodies such as upper stages, but that it was less suited to non-traditional bodies such as smaller rockets and payloads that seem to generate fewer large fragments and more smaller ones. This is significant: the emerging "NewSpace" paradigm is likely to involve more frequent launches of smaller payloads and/or use of smaller rockets in future.

The meeting then switched to considering studies of dust grains themselves. **Martin Suttle** (University of Pisa) presented a study of large silicate micrometeorite grains collected on Earth. In this context, large means between a few hundred microns and millimetres across. He reported that modelling (Genge *et al.* 2016) showed that metal beads formed in these objects when molten and, depending on the viscosity, could reach the surface and even be lost. This effect was largest for larger grains. He also reported that at the larger sizes the fraction of non-spherical objects grew (to a few %), which he assigned to aerosculpting of the hot objects during their atmospheric passage combined with high shear strengths of the silicate melts.

Geoff Evatt (University of Manchester) then reported on how to find micrometeorites in the Antarctic ice. Combining data from various sources, he predicted that between 32 and 62 meteorites of over 60 g mass impact every year per million km² of ice cap. But if some of the objects recovered on the ground are fragments from one body that broke up during atmospheric entry, then the number of bodies arriving from space at the top of the Earth's atmosphere is smaller than the prediction. You could just compare the flux at Antarctica with that elsewhere, but is this a constant value at all latitudes? Modelling suggests it isn't, and he compared data for observations of fireballs in the skies vs latitude with his model. After some more modelling, he predicted the meteorite influx per unit area at the equator was some 50% greater than at the poles.

> **"There might be one interstellar micrometeorite in every 30 or 40 kg of chalk"**

Interstellar dust

Matt Genge (Imperial College London) then discussed whether part of the terrestrial micrometeorite influx could have an interstellar origin. It has long been known that small grains of interstellar dust reach deep into the solar system (e.g. Grün *et al.* 1993), and indeed some likely examples have been captured in space and returned to Earth by NASA's Stardust mission (Westphal *et al.* 2014). Genge pointed out that recent work on 89 Myr old chalk samples showed that yields of 80 micrometeorites per kg can be achieved (Suttle and Genge *et al.* 2017); he wondered if any were interstellar. He first calculated the likely flux at 1 au as a function of particle size, along with any solar focusing effects and the speed relative to the Earth. Allowing for different angles of entry into the atmosphere, he then calculated atmospheric entry survival rates for grains of different sizes, with silicates and corundum as examples. He concluded that there might be one interstellar micrometeorite in every 30 or 40 kg of chalk. Of course, this rate will vary with the age of the host rock. The influx of material is time dependent as the Sun moves through the local interstellar medium and concentrations would have been higher in periods when the Sun moved through dense molecular clouds, for example. Given that the oldest recovered micrometeorites are over 2 Gyr old, Genge proposed that if examples of interstellar micrometeorites could be recovered and identified from the rock record, then it might be possible to plot the history of the density of the interstellar medium the Sun had passed through.

The final talk of the day was by **Leon Hicks** (University of Leicester), who reported on synchrotron nanoprobe analyses of some dust grains from asteroid 25143 Itokawa (an S type asteroid). In 2010, the Japanese mission Hayabusa returned grains from the surface of Itokawa (e.g. Nakamura *et al.* 2011) and these are now being studied widely. It was recognized early on that not only was the surface material of Itokawa heavily influenced by impact-related shocks, but also by space weathering (e.g. Noguchi *et al.* 2011, 2014). This presents an opportunity to study space-weathering effects on the rims of dust grains and this is what Hicks reported for five dust grains. Four of the five grains were dominated by olivines, with the fifth showing as a low calcium pyroxene with high-calcium inclusions (reflecting the prevalence of such materials on Itokawa). Using the Diamond synchrotron, Hicks was able to show that the samples had affinities with LL5/LL6 chondrite materials. Amorphized rims on the grains between 10 and 100 nm thick showed space-weathering effects, illustrating the sensitivity of this technique at small scales (Hicks *et al.* 2019). In future, the technique can be applied to any grains collected in space, even on returned dust collectors such as the proposed ODIE (see above) where the dust is collected via an impact process.

Overall, the meeting showed that there is a major interest in the UK in dust near the Earth, both for scientific and technical reasons. Given that both NASA and ESA data show a growing debris contribution, and that damage due to accidental impacts is already occurring, it is safe to say that we can expect more high-profile incidents in the near future. ●

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