Specialist Discussion Meeting Report

Blowing Hot and Cold: The Plumes of Io and Enceladus

Penelope J Wozniakiewicz, Mark J Burchell and Andrew J Coates report on the RAS Specialist Discussion Meeting devoted to the topic of sampling the naturally occurring plumes at Io and Enceladus.

Exploring the myriad of satellites surrounding the giant planets in the outer solar system is one of the major goals of planetary science. The gas and ice giant planets are fascinating in their own right, but the host of small 'worldlets' that orbit them offer many insights into the physical processes that govern planetary formation and evolution.

Io at Jupiter and Enceladus at Saturn are not only different from each other (Io's surface is rocky while Enceladus is icy), but their similarities to each other mark them out as different from the other satellites, in that they naturally expel material from their interiors into space.

In the case of Io, this is via the extensive volcanic activity across the whole surface, which emits plumes of volcanic material into space (Morabito *et al.* 1979). This arises from an interior heated by extreme tidal forces thanks to its eccentric Jovian orbit arising from Laplace orbital resonances with Ganymede and Europa.

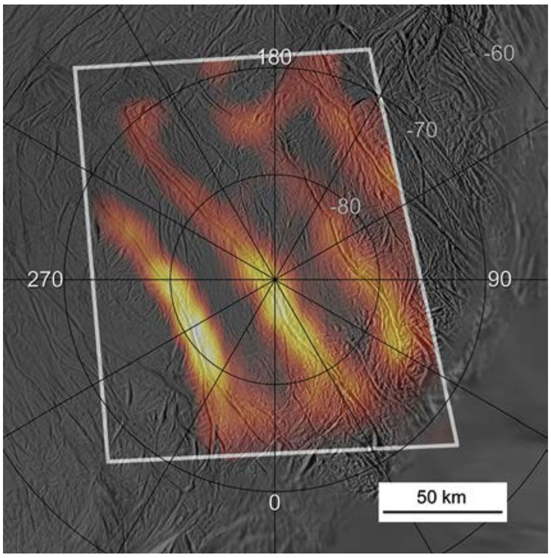
At Enceladus, the gravitational tidal forces are similarly complex, arising not just from the orbit around Saturn, but also a resonance with Dione. These serve to pump the moon's internal global ocean out through vents in the icy surface, forming spectacular plumes, particularly in the south polar regions (figure 1).

Both bodies can therefore not just be observed during flybys, but the plumes can actually be sampled (see Frank & Paterson 2002 for a report on ions from a volcanic eruption at Io, and Waite *et al.* 2006 for Enceladus). At Enceladus, this has led to many reports from the Cassini mission, and at Io there are reports not just from the Galileo mission of the 1990s, but also great hopes for major results from the various Jovian missions now underway or planned.

The outer solar system bodies feature as heavily in various strategies and roadmaps, such as the current US Decadal Survey for Planetary Science and Astrobiology (NASEM 2023), and the STFC Solar System Roadmap (de Moortel *et al.* 2023). It is perhaps no surprise therefore that many proposals are now specifically targeting Io and Enceladus in response to calls for new missions (e.g. in the NASA New Frontiers 5 programme or ESA's Voyage 2050 programme). These proposals often focus on sample capture, either for analysis immediately after capture at Enceladus, or even for sample return from Io. The key science goals differ. Samples from Io offer the chance to study material from the interior of a solid body, material possibly intimately involved in processes of rocky body formation and offering associated insights. At Enceladus, the water-rich plumes offer tantalising hopes for glimpses of the evolution of a possible niche habitable region. The December 2024 RAS 'G' specialist discussion meeting thus considered a range of current work relating to the plumes at both Io and Enceladus.

Enceladus

The morning session of the day was devoted to Enceladus. Nozair Khawaja (University of Stuttgart and Freie-University Berlin) gave an invited overview of the possible chemistry of the internal ocean at Enceladus based on results from Cassini's impact mass spectrometer (Cosmic Dust Analyzer – CDA) taken during various flybys.



1 *'Tiger' stripes near the south pole of Enceladus. This heat-map, obtained by Cassini, shows regions some 100 K hotter than the surrounding material, and from which geysers of water are typically emerging.* (NASA/JPL/GSFC/SwRI/SSI).

As well as confirming the presence of NaCl ice grains (Postberg *et al.* 2009), which, if they escape the local gravity, populate Saturn's E ring, CDA also found extensive evidence for both low- and high-mass organics present in the icy grains of the plume (Khawaja *et al.* 2019, Postberg *et al.* 2018, respectively); more recent analysis of mission data reveals evidence for phosphates (Postberg *et al.* 2023). The internal ocean thus contains five (CHNOP) of the six main biologically essential elements (S being the sixth) as well as evidence for complex organic chemistry. The speaker was thus not surprised that the recent ESA review for a new L4 mission, identified Enceladus as the main target (Martins *et al.* 2024). One key technical point that emerged, and was questioned by the audience, was that the mass spectra from CDA depends on the impact speed (and hence degree of breakup of the original organic compounds during the impact ionisation process) and this varied with each Enceladus flyby. This encounter speed issue was revisited in several later talks.

The next speaker, Jürgen Schmidt (Freie-University Berlin), also discussed CDA analysis of the Enceladus plume. Schmidt contrasted CDA data taken during the fast E5 (17.7km s^{-1}) and slow E15 (7.5km s^{-1}) encounters and also reported on flux data from the High Rate Detector (HRD) taken during the E7 and E21 encounters. Taken together, a new model of the plumes can be obtained, suggesting an ejection rate of 28 kg/s^{-1} at the South Polar Terrain. Also, the salt-rich grains in the model are smaller than previously reported (again, the CDA response changes with impact speed and this can be allowed for by comparing encounters at two speeds), and the ratio between salt and organic-rich grains has changed, with the salt-rich grains now contributing only 1% (or less) of the total mass. Moreover, where previous reports have referred to two populations of salt grains, salt-rich and salt-poor, these now appear to be one population.

As flagged by the previous speakers, what is observed in mass spectra from CDA for organic molecules is the product of the breakup of the molecule during the high-speed impact event. The molecules will break apart at specific points in their structures, and the resulting major fragments, along with the spacings between satellite peaks (which reveal which elements stick in groups to the main peaks) are what is observed, providing clues to the parent molecules and their chemistry. Understanding how organic molecules break apart is thus vital, especially given that, as already noted, it is impact speed dependent.

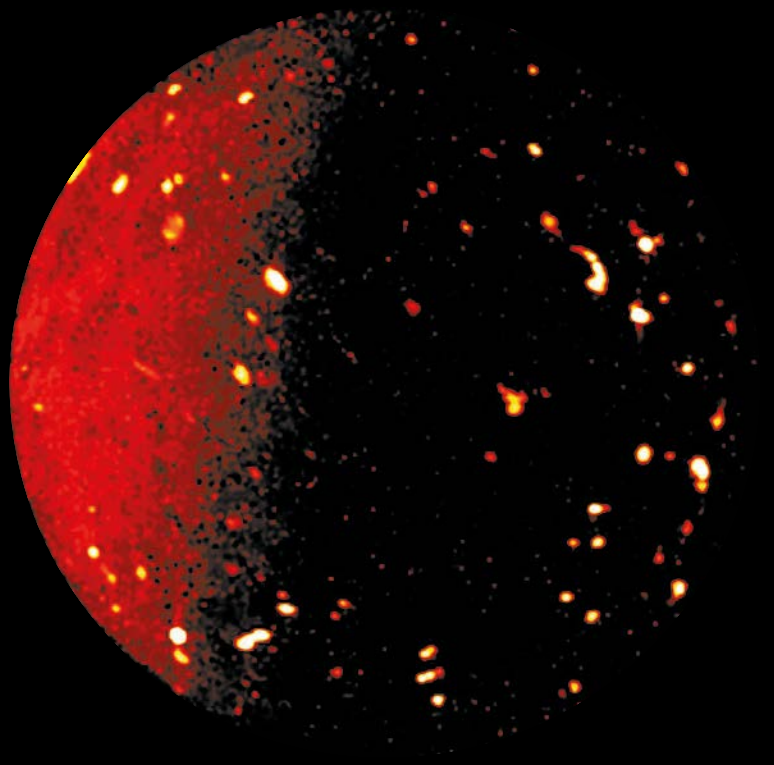
Thomas O'Sullivan (Freie-University Berlin) reported on work to model this process using quantum chemistry, and how these results compare to those from laboratory experiments using laser-induced liquid ion beam desorption (LILBID).

Using LILBID, specific known compounds can be frozen in ice and then mass spectra produced. The results so far indicate that the molecules do not necessarily preferentially break at the weakest bond, and that the water/ice interface with the molecules can likely influence the results. This sort of careful laboratory work is clearly essential to ensure correct interpretation of the data from space.

The talks then switched to another experiment on Cassini, with Anna Parsec-Wallis (MSSL) reporting on interpreting the results from the Cassini Electron Spectrometer (Coates *et al.* 2010).

This had reported the presence of anions in the Enceladan atmosphere, arising from low-mass clusters

Io key facts



A 2022 Juno image of Io in infra-red, showing the volcanic hot spots as white (NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM)

Discovered by: Galileo Galilei in 1610

Observed up-close by two space missions, Galileo (1990s) and Juno (since 2016), and more distantly by Pioneer 10 (1973) and 11 (1974), Voyager 1 and 2 (both in 1979, with Voyager 1 producing the first images of volcanic activity), and New Horizons (2007). The Juice (launched 2023) and Europa Clipper (launched 2024) missions currently flying to Jupiter are focused on Ganymede and Europa respectively, with no planned fly-bys of Io.

Size: 3rd largest Jovian satellite, and larger than the Earth's moon with radius approximately 1822km

Mean density: 3530kg m^{-3}

Orbits: Jupiter at roughly 422000km, with tidal bulges on the solid surface of ±100m

"Enceladus's internal ocean contains five of the six main biologically essential elements as well as evidence for complex organic chemistry"

of water ions. Although not abundant in the solar system, anions have also been observed around the Earth, at comets (Halley and 67P Churyumov-Gerasimenko) and at various moons of outer planets such as Rhea, Dione and Titan, and, in 2024, were reported near the Earth's moon. In the recent new analysis of the Cassini data, Parsec-Wallis confirms OH^- as the likely source of the anions, with another signal, possibly arising from H_2O^- or Cl^-, with Cl^- indicating the presence of salts; this awaits further clarification. Parsec-Wallis also described work to improve the electron spectrometer design, so that it would be suitable for a future ESA mission to Enceladus as proposed by Martins *et al.* (2024), for example.

Mark Fox-Powell (Open University), speaking on behalf of Rachael Hamp who was unable to attend, focused on how salt-rich ice grains, as reported by CDA at Enceladus, freeze when they are in a plume emerging into vacuum.

This is the consequence of the water starting in a relatively warm internal ocean and emerging rapidly into a much colder, low-pressure exterior. Their experimental efforts to reproduce this (at the ISIS

Enceladus key facts

Discovered by: William Herschel in 1789
Observed up-close by: the Cassini mission in the early 2000s, with the discovery of plumes reported in 2005 which are now recognised as the source of Saturn's icy E ring. Also observed in some detail by Voyager 1 (1980) and 2 (1981).
Size: 6th largest Saturnian satellite, and much smaller than the Earth's moon with radius approximately 250km
Mean density: 1610 kg m^{-3}
Orbits: Saturn at roughly 238000km, with tidal bulges on the solid surface of ±100m

Saturn's icy moon Enceladus with the plume of ice particles, water vapour and organic molecules that sprays from fractures in the moon's south polar region (NASA/JPL-Caltech)

neutron source at Harwell) led to a surprising discovery: a new low-temperature NaCl dihydrate, distinct from the well-known hydrohalite (Hamp *et al.* 2024), and which is formed when rapid freezing occurs at high cooling rates (flash freezing). It seems the effect is cooling-rate-dependent, with low rates producing the well-known hydrohalite, whereas with high cooling rates the new dihydrate was produced. The new dihydrate has distinct near-IR and Raman spectroscopic signatures, so can be readily identified if present. Ongoing work concerns how stable the new dihydrate is, and if it will survive at Enceladus and awaits discovery there.

The focus of the next two talks was laboratory production and studies of organic microparticles as proxies to be used in calibration of instruments in space. First, Steve Armes (University of Sheffield) described the importance of having appropriate analogues of organic particles.

This group has long supplied organic microparticles to other groups for instrument calibration, e.g. impact ionisation detectors (see Fielding *et al.* 2015 for a review). More recently attention has focused on polycyclic hydrocarbons, and Armes described the synthesis of phenanthrene/pyrene mixtures, and how they had been used in high-speed light gas gun experiments, resulting in craters in metal targets and captured grains in ultra low-density aerogels (Brotherton *et al.* 2024). A key result is that the two components of these particles behave differently during capture, with, for example, the Raman signals from the lower melting point phenanthrene disappearing after what, at first appearance, was apparent intact particle capture in aerogel. This suggests that strong impact speed specific capture effects can be present when sampling organic materials in flybys at high speeds.

"Strong impact speed specific capture effects can be present when sampling organic materials in flybys at high speed"

Min Zeng (University of Sheffield), continuing the theme of synthesis of PAH microparticles, reported on the production of nitrogen-rich PAHs (i.e. PANHs), where one or more N atoms is present in a fused carbon shell.

PANHs have been widely reported by astronomers as present in starburst-dominated galaxies and have recently been observed in the interstellar medium. It seems important therefore to have them in our collections of microparticle analogues for laboratory studies of impact processes likely to be involved with collecting organic-rich dusts at high speed, such as an Enceladus flyby. Zeng thus described the synthesis of PANH microparticles and how they had then been coated with thin overlayers of Polypyrrole (PPY). The PPY is highly conducting, and can be readily charged, making the microparticles easy to use in electrostatic accelerators such as those often used to calibrate impact ionisation mass spectrometers. The results of such calibration studies are eagerly awaited.

Gillian Sclater (Birkbeck College) spoke about clathrates. These are lattice like atomic or molecular structures which can trap other atoms or molecules in their interiors. They can be thermodynamically stable under high pressures and low temperatures, but if their ambient conditions change, they can break down, releasing their trapped contents.

The reported high gas content in the Enceladan plumes may arise from such a breakdown of clathrates. Sclater described a model based on this process which may drive the plumes at Enceladus. For a variety of flow rates and assumptions about vent shape etc, the model was able to predict plume speeds and conditions and obtain broad agreement with what is observed at Enceladus, although the associated Mach numbers are higher than those generally in the literature.

The morning session then closed with three rapid talks describing posters that were on display during lunch. **Angus Aldis** (Open University) described investigations into plumes from hot springs in Iceland, which were used as an analogue for Enceladus. The patterns in which plume aerosols dispersed spring material were studied, and there is ongoing research into the organic and biological content of the deposited materials. **Jessica Hogan** (Open University) presented work on observations of salt-rich droplet freezing made in the Aarhus wind tunnel at low pressures. Such work is vital to properly understand what happens in the vents in the ice that produce the Enceladan plumes. **Duncan Lyster** (University of Oxford) presented the design for a thermal imager that can produce a multiband map of the Enceladan surface. The low mass and light weight design (based on past instruments, so it already has space heritage) should produce high resolution maps with 80m per pixel resolution from an altitude of 150km. The intention is to get the design ready for a possible future mission opportunity when it arises.

Io

After lunch, attention turned to Io with an introductory talk by invited speaker Ryan Ogliore (The Washington University in St. Louis), who began by giving an overview of volcanism on Io, then focused on one volcano, named Prometheus, giving details of the plume (which gives its name to a class of plumes of similar height, i.e. Prometheus-type plumes), including height (75–100km), particle size, total mass in the plume, etc.

These plumes are thought to arise from the interaction of silicate magmas with near-, or sub-, surface sulphur (Consolmagno 1979, and see below). Ogliore noted that the plumes are located in discrete locations, and all relevant observations of plumes, from Voyager 1 in 1979 to the latest images today, show evidence for the plume from Prometheus, suggesting continual eruption over a lengthy period. This is an important point when planning future missions.

Modellers have concluded that, based on the brightness of the plumes and their heights, particles of up to 10s of microns must be present. Indeed, based on comparisons to lunar volcanism, there may be glass beads of size around 50µm present in the plumes. Mie scattering studies provide a lower estimate of plume mass, but these are not sensitive to larger grains, which have to be allowed for separately. Doing this, based on the available evidence, in the Prometheus plume there may be a column density of between 0.1 and 100mg cm^{-2}, depending on how many larger grains are present, with suggested outflow rates of 5×10^6kg s^{-1} and a total mass at any time of some 2.5×10^9kg. This suggests a 100cm^2 collector (similar to that flown on the Stardust mission to comet Wild 2; see Brownlee *et al.* 2006) would capture between 100mg and 100g of pyroclastic material from a transit of the plume, with grain sizes up to 10 or 50µm. Ogliore then asserted that you would need to return them to Earth to do the requisite detailed analysis, accessing instrumentation of greater sophistication, precision and accuracy than can be provided *in situ* on a spacecraft. Ogliore believes this thus mandates a sample return mission, which needs six years to get there, and three more to return, with a single pass by Io at some 7+ km s^{-1} being sufficient to collect enough sample material.

As with any sample collection from a plume, Ogliore pointed out that you have to balance the sample collection with not destroying the spacecraft during its high-speed encounter with the plume material. Bumpershield designs are proving sufficient to do this in tests, but as with the NASA Stardust mission, after new observations are made just before the encounter, small changes in trajectory can be made to minimise the risk whilst maximising capture rates. This would also permit targeting a new plume in the unlikely event that Prometheus has 'turned off' after launch.

An Io sample return mission could answer many questions. Are the materials representative of the early proto-solar nebula in the region of Jupiter? How did Io's core form? Did Io form with an icy surface like some other similarly sized bodies around Jupiter? How do young rocky terrestrial planet-sized bodies evolve from magma-ocean-rich to solid surfaced bodies and how does this relate to exoplanet systems? As well as solid (dust grain) samples, a mission will also be able to capture gas and ions in the plume and plasma torus, thus accessing three of the four states of matter. This will provide a more detailed understanding of how the Io plasma torus formed, for example.

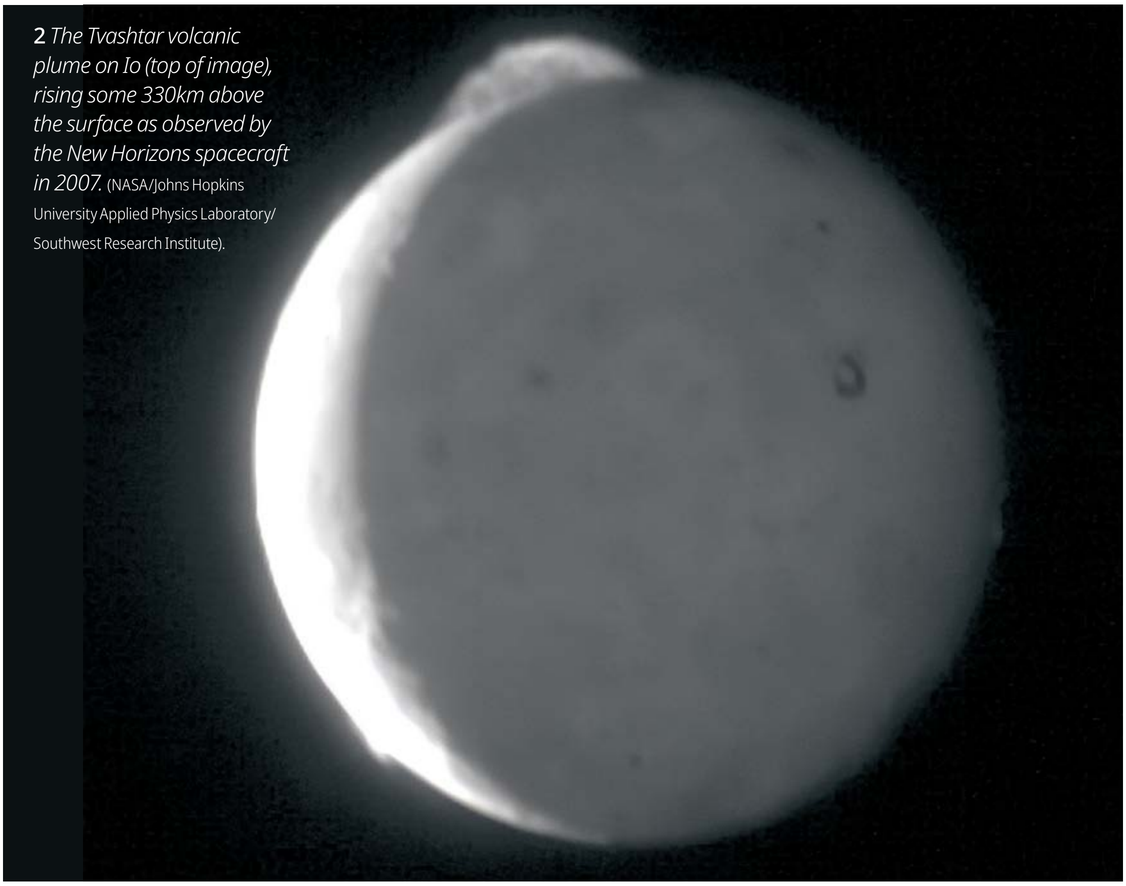
"As well as solid, dust grain samples, a mission will also be able to capture gas and ions in the plume and plasma torus, thus accessing three of the four states of matter"

Ogliore then considered how to analyse the captured materials to address these questions. The view was that, given that over 90% of the material is likely to be bulk silicate-rich Io grains, combined with the nature of the analysis (involving precise, sensitive isotope chemistry), the resulting analysis will not be grain-by-grain as with the Stardust mission, but will mostly be bulk studies, trying to average over whole samples. This is a new challenge, and Ogliore has been organising laboratory impact experiments to determine which are the best collector substrate materials to capture the dust samples at appropriate speeds. So far the team has been testing with powdered Hawaiian glass and Murchison meteorite samples as projectiles, fired in the two-stage light gas gun at the University of Kent into targets such as germanium wafers, solid metals (aluminium, gold and indium), plus nano-porous silicon, porous metal foams, aerogel and so on. This will validate both the collection and analysis methods, permitting selection of, say, the four best collector materials, and show that the analysed data will be sufficient to address the science questions. However, even when this is complete, a full programme of more detailed tests of the selected capture media is then needed, testing not just the media in general, but the ability to capture as wide a range of potential impactors as possible and not just the two used so far.

The speaker's enthusiasm was evident to all, as was the scale of the work needed to prepare a detailed, viable mission proposal for a future NASA call. The essential laboratory studies to underpin such a proposal are clearly vital, and need to be done now, in advance of such a mission being selected.

Lionel Wilson (Lancaster University) addressed the mechanisms behind the violent explosive volcanic activity present on Io.

Wilson pointed out that the laws of nature behind such eruptions (i.e. on silicate bodies there is melting in the mantle, with transfer of magma and exsolved gases rising through fractures and erupting) must be the same as elsewhere, but the influence of the local environment will be critical. For example, there is lower gravity on Io (so ejected material can rise higher). The acceleration of the material entrained in the emerging gas will also be affected by the local conditions, particularly the ambient pressure at the surface. Thus, models of the process must account for these conditions. However, it is not as simple as that. For example, in the plumes the gas pressure falls on Io such that the solid material and gas decouple, stopping the acceleration. Once this is properly allowed for, most of the intermediate height (5km) fire fountains on Io can be explained, but the extremely tall Pele-type plumes (after the Pele volcano on Io from which 290+km plumes emanate; see figure 2), cannot. The solution is that Io undergoes continual resurfacing, moving old surface material to depth, where it is geothermally heated. Any SO_2-rich material then melts, and if rising magma intersects such a reservoir, they mix, changing the thermo- and gas- dynamics of the rising material. The consequences include not only higher ejection speeds, and hence the great height achieved in such plumes, but also the silicate materials form a greater volume of the plume than otherwise, with particles up to 100µm in size, similar to those on the Moon at the Apollo 17 landing site. The ratio of the frequency of the 5km to 250km plumes thus indicates the distribution of these SO_2 reservoirs in the interior of Io. Also, the decoupled gas and solid materials may fall back to the surface separately, with different radial distributions on the surface around the launch site. More work is



2 *The Tvashtar volcanic plume on Io (top of image), rising some 330km above the surface as observed by the New Horizons spacecraft in 2007.* (NASA/Johns Hopkins University Applied Physics Laboratory/ Southwest Research Institute).

underway to understand the detailed mechanisms of the mixing of the recycled surface material and rising magmas, as well as its consequences.

Mark Burchell (University of Kent) spoke about the nature of the spacecraft orbit needed to sample a plume at Io.

Burchell described the options, ranging from one-off flybys (either heading out of the solar system, such as with the various Pioneer, Voyager and New Horizons missions) or a heliocentric orbit which brings the sample back to Earth as discussed by Ogliore. Equally, one can enter orbit around Jupiter and have multiple flybys of Io, such as by the Galileo and Juno missions. More adventurously still, one could orbit Io itself, but this is not highly recommended as orbital stability will be poor given the various perturbing bodies nearby, and the presence of the intense Jovian radiation fields that will rapidly 'cook' the spacecraft electronics. All of these types of spacecraft orbit have characteristic Io encounter speeds, which Burchell estimated as ranging from 1 to 10+km s^{-1}. Burchell then modelled the associated peak shock pressures for various example projectile materials (basaltic glass and olivine) encountering different collector materials (including solid metals and aerogels of various densities) and described the consequences for the state that the material will be in when retained. For comparison, Burchell also showed typical capture speeds and shock pressures recently calculated for Enceladus (Burchell & Wozniakiewicz 2024). This addresses the point made by many of the earlier speakers about Enceladus but which is also relevant to Io; namely the material captured by instruments on a spacecraft can be highly altered as a result of the high-speed encounter, and this needs to be understood when planning missions and the sample analysis. Burchell finished by commenting that, interestingly, in the literature about Io and Enceladus encounters, many papers or mission proposals give the altitude of the closest approach but often ignore the encounter speed.

The final speaker was Xiaodong Liu (Sun Yat-sen University Guangdong) who talked about what happens to the plume material that escapes from Io.

As noted earlier in the day, at Enceladus the equivalent material populates Saturn's E ring. But what happens at Io? The particles from Io are charged during the ejection process and then accelerate around the Jovian system. A suitable charging model has been developed and applied with a model of the consequent dynamic motion around Jupiter. The results show significant implantation of the material from Io onto Europa, Ganymede and Callisto for example (with rates of 10s to 100s of kg yr^{-1}). The speaker then described how the material is distributed differently on each body, covering the entire surface of Europa, but favouring the anti-Jovian quadrant on Ganymede and Callisto. The presence of this material may be altering the surface chemistry of these bodies, and this may be detectable by current and future missions.

Conclusion

The meeting ended with the audience greatly enthused by what they had heard. A new state of matter (the NaCl dihydrate), synthesis of novel microparticles (mixed PAHS and PAHNs), the fate of material ejected from Io and how much ends up on other Jovian satellites, just to name a few. The day had included results from an eclectic mix of planetary science, chemistry, geophysics, orbital mechanics and a field trip to Iceland, with speakers from not just the UK but the US, Germany and China. This illustrates both the range of the knowledge needed to properly interpret bodies in the solar system, and the multi-national nature of the groups working on these issues. The need for basic laboratory science and modelling to help both plan future missions and explain the results obtained from past and present missions, was clear to all. ●

AUTHORS

Penelope Wozniakiewicz (p.j.wozniakiewicz@kent.ac.uk) is senior lecturer in space science at the University of Kent. She is interested in cosmic dust, specialising in collecting it in space, and on Earth from extraordinary locations, from tropical islands to the roof of Canterbury cathedral.

Mark Burchell (m.j.burchell@kent.ac.uk) is emeritus professor of space science at the University of Kent. He specialises in hypervelocity impact studies and worked on the NASA Stardust sample return mission (amongst others).

Andrew Coates (a.coates@ulc.ac.uk) Andrew Coates is professor of physics and deputy director (solar system) at UCL's Mullard Space Science Laboratory (MSSL). His scientific interests include the solar wind interaction with planets and comets, planetary surfaces and space instrumentation.

REFERENCES

Brotherton EE *et al.* 2024 *J. Am. Chem. Soc.* **146** 20802
Brownlee DE *et al.* 2006 *Science* **314** 1711
Burchell MJ & Wozniakiewicz PJ 2024 *Meteoritics & Planet. Sci.* **59** 1385
Coates AJ *et al.* 2010 *Icarus* **206** 618
Consolmagno GJ 1979 *Science* **205** 397
de Moortel I *et al.* 2023 *A&G* **64** 3.34
Fielding LA *et al.* 2015 *Chem. Comm.* **51** 16886
Frank LA & Paterson WR 2002 *J. Geophys. Res. Space Phys.* **107** 1220
Hamp RE *et al.* 2024 *J. Phys. Chem. Letts.* **15** 12301
Khawaja N *et al.* 2019 *MNRAS* **489** 5231
Martins Z *et al.* 2024 *Report of the Expert Committee for the Large-class mission in ESA's Voyage 2050 plan covering the science theme 'Moons of the Giant Planets'* ESA/Science Office
Morabito LA *et al.* 1979 *Science* **204** 972
NASEM 2023 *National Academies of Sciences, Engineering, and Medicine Origins,Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032* Washington, DC: The National Academies (doi.org/10.17226/26522)
Postberg F *et al.* 2009 *Nature* **459** 1098
Postberg F *et al.* 2018 *Nature* **558** 564
Postberg F *et al.* 2023 *Nature* **618** 489
Waite JH *et al.* 2006 *Science* **311** 1419