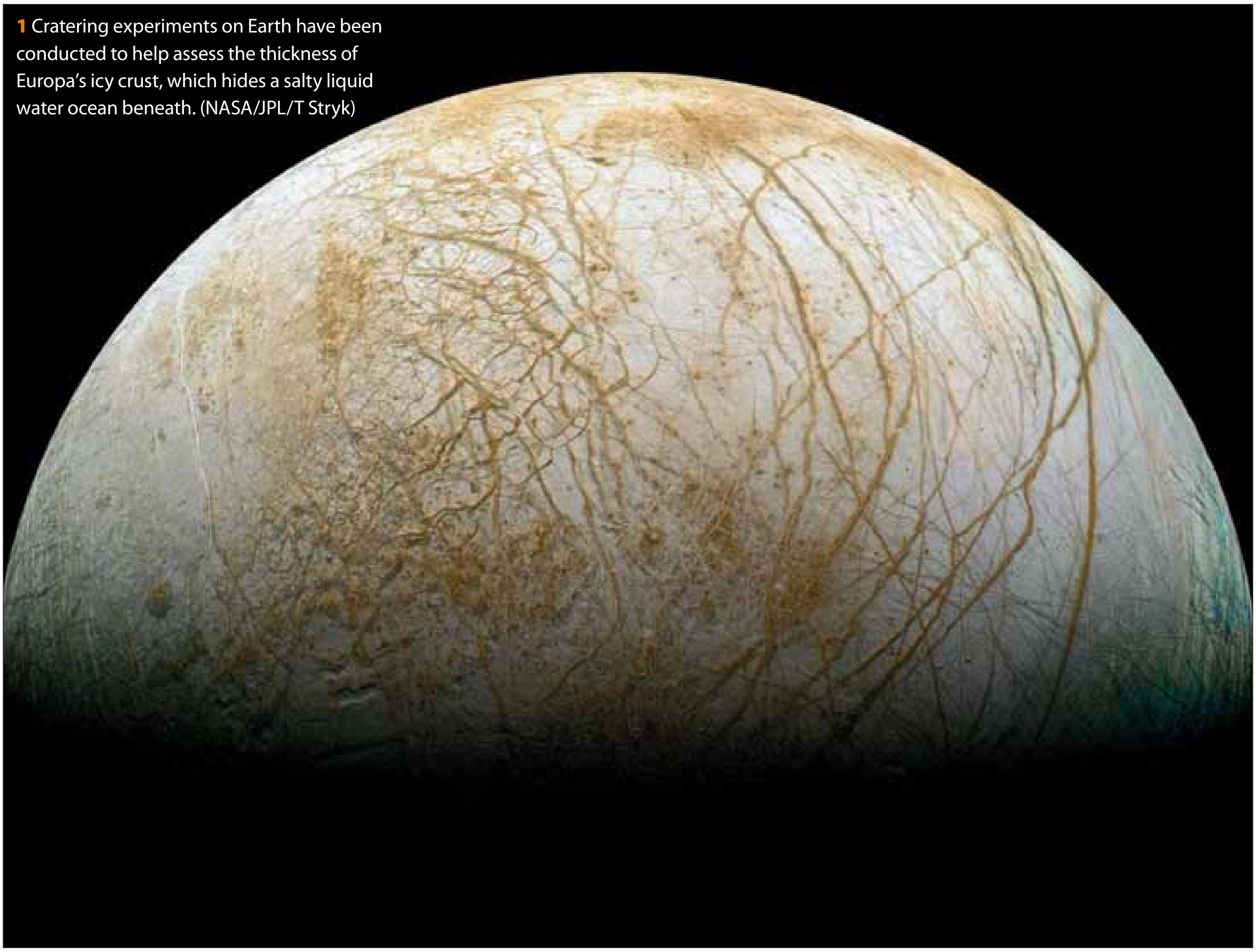


1 Cratering experiments on Earth have been conducted to help assess the thickness of Europa's icy crust, which hides a salty liquid water ocean beneath. (NASA/JPL/T Stryk)

Frozen bodies and landscapes

Kathryn H Harriss reports on "Frozen worlds and landscapes of our solar system", a meeting that demonstrates the breadth and depth of UK interest in icy moons.

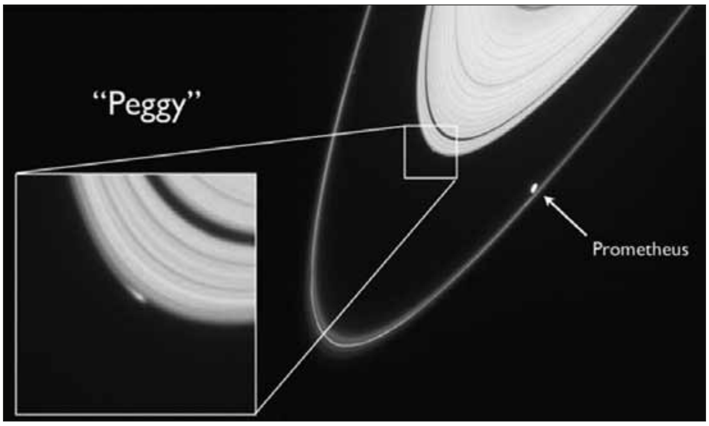
Exploratory space missions since Voyager have discovered abundant solar system bodies and landscapes that are dominated by ice, beyond the snow line, but also on the inner planets including Mars and Mercury (Mustard 2001 *et al.*, Vasavada *et al.* 1999). Recent images from the New Horizons mission have shown ice on Pluto and Charon (Moore *et al.* 2016), and Rosetta images have identified ice regions on comet 67P/Churyumov–Gerasimenko (Barucci *et al.* 2016). This has helped to grow significantly the research field investigating the various ice regions and ice interactions on different bodies. The aim is to better understand the formation of these bodies and their structure, climate and surface activity.

"The aim is to understand the formation, structure, climate and surface activity"

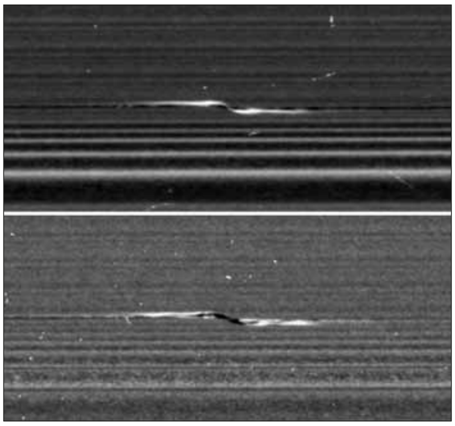
The increase in evidence about multi-layered ice-covered bodies led to my own research to investigate impact cratering on these surfaces (Harriss & Burchell 2017), which ignited my interest in ice bodies. This led in turn to the idea of exploring the study and characterization of these landscapes and bodies through an RAS Specialist Discussion Meeting, which was held on 9 December 2016.

Icy bodies at Saturn

The meeting began with **Carl Murray** (Queen Mary, University of London), who spoke about observations of the saturnian system from the Cassini probe, a joint mission between NASA, ESA and ASI that sent



2 Peggy, a bright smudge at the edge of the A ring, shown on an image that also includes the moon Prometheus and the F ring. (NASA/JPL-CALTECH/SSI)



3 A propeller feature in Saturn's A ring. The top image is looking towards the rings' sunlit side, the bottom image shows the unilluminated side. (NASA/JPL-Caltech/Space Science Institute)

back data and images from its arrival at the Saturn system in 2004 until its controlled plunge into the planet in September 2017. The mission included the Huygens lander, which successfully touched down on the surface of Titan (Lebreton *et al.* 2005, Zarnecki *et al.* 2005). Murray joined the Imaging Science Subsystem Team (ISS) on the mission in 1990, and provided a fascinating talk about the outcomes from the imaging science of Cassini. He reviewed what is known about the local structure of the rings and moons which perturb them, including the moon Peggy, which appears to be undergoing rapid evolution, possibly as a result of collisions (Murray *et al.* 2017).

"The goal is to construct a 3D diagram of the martian south polar region"

The orbiter carried several imaging instruments besides the ISS, including the Composite Infrared Spectrometer (CIRS), Ultraviolet Imaging Spectrograph (UVIS), and Visible and Infrared Mapping Spectrometer (VIMS). Other instruments studied the dust, magnetosphere, and radio and plasma waves. The data from Cassini have been scientifically significant for the understanding of the interaction between the rings and the moons that orbit Saturn. The rings are primarily composed of water ice and are affected by a combination of self-gravity, collisions and gravitational perturbations from embedded or nearby satellites. One of the major outcomes from the Cassini–Huygens mission is the observation and understanding of ring behaviour. The F ring of Saturn was first discovered by the Voyager 1 mission (Murray *et al.* 1997) and is a multistranded system theorized to have formed from the collisional and gravitational effect of small satellites, including Prometheus (Murray *et al.* 2005) and Pandora, its two shepherding moons. But the actual mechanisms that operate are unknown (Murray *et al.* 2008). The system is also theorized to be relatively young, (~10^6 years), and to have resulted from the disruption of a moon by a collisional event.

Images from 2013 obtained with the ISS observed an object perturbing local material on the outer edge of Saturn's A ring. This appears to be the formation of a new moon, provisionally called Peggy (figure 2), which has since been indentified in 2012 images too. It is possible that Peggy represents the end product of the evolution of "propeller" structures, as proposed by Tiscareno *et al.* (2006) and shown in figure 3, escaping from the A ring (Murray *et al.* 2013). More recently, Peggy appears to be no longer alone: a second object has been observed trailing it (Murray *et al.* 2017).

In the second talk, **Geraint Jones** (UCL Mullard Space Science Laboratory) discussed surface charging of Saturn's moons. Many of them reside within Saturn's magnetosphere and therefore are continuously exposed to the magnetosphere plasma. The bodies are also illuminated by ultraviolet light, and it is the presence of both that results in the surface charging, which data from the Cassini Plasma Spectrometer (CAPS) indicates could affect the movement of fine-grained surface material. Moons that have shown surface charging include Hyperion (Nordheim *et al.* 2014) and Rhea (Roussos *et al.* 2012).

Enceladus has particularly interesting chemistry and an unusual environment. **Emmal Safi** (Keele University) touched upon the chemistry, presenting her work on laboratory studies of clathrate hydrates observed on Europa and Enceladus (Bouquet *et al.* 2015, Prieto-Ballesteros *et al.* 2005). It is possible that such clathrates – cage-like structures of water molecules encasing gas molecules – may be responsible for altering the surface geology of these bodies. Safi investigated this with experiments to better understand the effect of salts on the formation of clathrate hydrates using synchrotron X-ray diffraction at the Diamond Light Source in Oxfordshire (Safi *et al.* 2017). The experiments studied the *in situ* formation of CO_2 clathrates in a model subsurface ocean environment replicating that expected at Europa or Enceladus. The samples were also thermally cycled to recreate possible tidal effects and seasonal variations. Salts proved to have an inhibiting effect on clathrate formation and at some compositions and concentrations affected their structure.

Ice on Mars

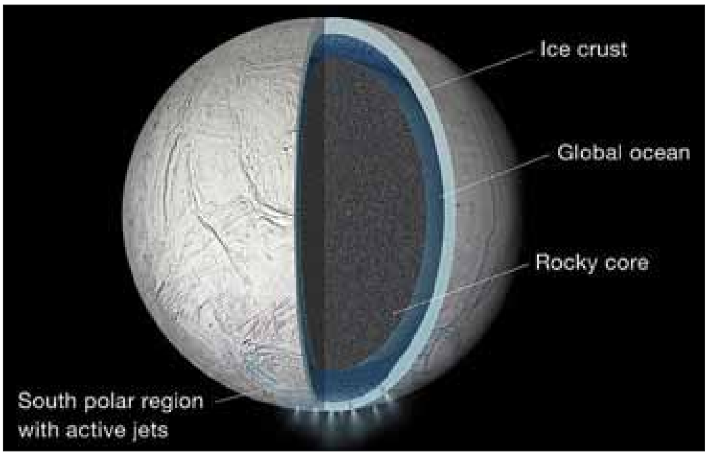
The second part of the morning focused on ice environments on Mars from poles to theorized permafrost (Phillips *et al.* 2008, Ogawa *et al.* 2003). The first three talks of this session concerned aspects of the martian southern polar ice cap, given by PhD students working at Mullard Space Science Laboratory (MSSL).

The polar region has been extensively covered by instruments on NASA's Mars Reconnaissance Orbiter (MRO), including the Shallow Radar (SHARAD). **Si-Ting Xiong** (MSSL) used images from SHARAD to investigate the internal stratigraphy of the southern polar region, along with the Mars Advanced Radar for Subsurface and Ionosphere sounding (MARSIS) on ESA's Mars Express orbiter. The goal is to construct a three-dimensional block-diagram of the martian south polar region, which will help to understand the interactions between subsurface and surface processes such as the slow annual accumulation of CO_2 ice and the role of dust storms.

This work complements that presented by **Alfiah Rizky Diana Putri** (MSSL), who discussed mapping and detecting changes to the southern polar ice cap. This area retains a layer rich in CO_2 that, in the northern polar region, sublimates each summer. Though there appears to be little seasonal variation around the south pole, Putri has identified small changes including the creation of features known as "spiders" and "Swiss cheese" terrain (figure 4); she also worked on layers on the edges of the ice cap. This work used observations from multiple instruments; images had to be referred to a global reference system in order to match and compare locations.

Jacqueline Campbell (MSSL) then spoke about compositional characterization of

4 (a) Mars Orbiter Camera image of the "Swiss cheese" surface features of the martian southern polar cap during the southern spring; November 1999, 1.5 m/pixel. (NASA/JPL/Malin Space Science Systems) (b) Image from HIRISE showing the spider features in a variety of terrains; 1 January 2009, 98.6 cm/pixel. (NASA/JPL/University of Arizona)



5 Artist impression of the internal structure of Enceladus. Icy moons such as Europa and Enceladus are of increasing interest due both to the complicated structure and the potential for life implied by the presence of water. (NASA/JPL-Caltech)

the residual cap at Mars's south pole. As the layers sublimate during the summer, the dust and particles they trapped are released and can be analysed, including any organic molecules. This work focused on the analysis of the dust rims created in the Swiss cheese regions (figure 4a), with a particular interest in the detecting of polycyclic aromatic hydrocarbons (PAHs). PAHs may play a role in abiogenesis (Zolotov *et al.* 1999), and would have been destroyed by surface processes elsewhere on Mars. The research used data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on MRO. The results were compared with known martian mineralogy and PAH laboratory data, and show that magnesium carbonate dust is present. The H_2O and CO_2 signals proved to be a limiting factor when looking for PAH signatures.

Ice is thought to have existed in the past in other areas of Mars too, and has left indications in the surface and geology of the planet comparable to glacial features observed on Earth. **Frances Butcher** (Open University) discussed her work investigating possible esker features associated with extant glaciers, with evidence for geothermal control upon recent basal melting of glaciers on Mars. It has been theorized that during the past 1 Ga, the cold and arid climate meant that water ice within the debris-mantled glaciers has stayed frozen and not produced meltwater (Head *et al.* 2010, Marchant & Head 2007). However, recently identified sinuous depressions, described as eskers, could have been produced by sediment deposition in subglacial meltwater conduits. New images from the High Resolution Imaging Science Experiment (HIRISE) have opened up this idea for further investigation. Butcher has identified two candidate eskers associated with young (<1 Ga) glaciers, which provide strong evidence for recent basal melting at the mid altitudes on Mars, and that geothermal heat flow exerted a strong control on the production of basalt meltwater in this region.

"These ice bodies could host the chemistry required for life to develop"

Impacts on icy bodies

There are many icy bodies (particularly small ones) in our solar system, and understanding how they react and change through common processes is required to understand their evolutionary history. Impact is a major geological process for icy bodies and was the subject of the first part of the afternoon session.

Kathryn Harriss (University of Kent) presented recent laboratory work investigating impacts on ice bodies. Previously, the University of Kent Impact Group and others have investigated impacts on solid ice bodies of different composition and for different impact scenarios (e.g. Croft 1981, Kadono & Fujiwara 1996, Burchell & Grey 2001, Grey *et al.* 2001, 2002, Shrine *et al.* 2002, Giacomuzzo *et al.* 2007, Miljkovic *et al.* 2011). The work presented by Harriss investigated impacts into heterogeneous ice targets which had an ice crust above material of different density: water, sand or basalt.

The aim was to recreate possible planetary scenarios including impact on icy bodies with a subsurface ocean (Carr *et al.* 1998, Hussmann & Wieczerkowski 2002) (figure 5), and investigate the effects of changes in subsurface density and thickness of the overlying ice crust. This may help to determine if craters on icy moons such as Enceladus or Europa can provide information about the ice crust thickness or subsurface density (Harriss & Burchell 2017). Similarities were discovered between craters formed by impact on ice over water and those observed on the surface of Europa. This work has shown that the thickness of the ice relative to the projectile has a significant effect; penetrating craters are smaller but deeper than non-penetrative craters. Of course, many other variables can change the characteristics of a crater, but understanding the effects of the thickness of the surface layer is valuable.

Mark Burchell (University of Kent) reported on an investigation of the catastrophic disruption of liquid-filled ice spheres, analogous to ice moons with a subsurface ocean, in order to create more realistic models of known bodies. This work explored the process of penetration in scenarios that produced non-penetrative cratering, penetrative cratering, and catastrophic disruption of the target by surface fracturing. Initial experiments indicated that below an energy density of $13\,\mathrm{J\,kg^{-1}}$, a non-penetrative crater is produced, between 13 and $15\,\mathrm{J\,kg^{-1}}$ a penetrative crater results and, at around $15\text{–}18\,\mathrm{J\,kg^{-1}}$, disruption of the target occurs. Laboratory experiments using the same size projectile found that $18\,\mathrm{J\,kg^{-1}}$ is required for disruption of a solid ice body. It was also noted that subcritical impacts produced faulting that permitted ejection of curtain-like plumes of water from the interior, of interest to those seeking to sample subsurface oceans in the search for life.

These ice bodies could host the chemistry required for life to develop; complex organic molecules have been observed on ice-rich comets such as Wild-2 (Sandford *et al.* 2006) and 67P Churyumov–Gerasimenko (Capaccioni *et al.* 2015), and by analysis of impact debris, as in the Deep Impact mission to comet Tempel-1 (A'Hearn 2005, Lisse *et al.* 2006, Holsapple & Housen 2007). However, another way to investigate the composition of a surface is by analysing the impact light flash. Light flashes are a useful tool that have been observed on the surface of the Moon; they can last up to a minute depending on the magnitude of the impact. **Jon Tandy** (London Metropolitan University), working in collaboration with the University of Kent Impact Group, presented a spectroscopic examination of the early stages of impact flashes using frozen lunar and martian regolith simulant, in order to examine the chemical behaviour of the energetic and short-lived light flash. Tandy set up an impact experiment using aluminium spheres hitting CO_2 ice at around 5 km s^{-1}, analysed by a high-speed spectrometer which recorded emission spectra during the first 10 μs after impact. This work was a scoping exercise and proved to be successful. Future work will include validating these results and varying impact variables such as projectile size and impact speed and, if possible, begin to use ice mixtures to determine if constituents of icy surfaces can be analysed in this way.

"This is a growing field, with future missions to icy bodies carrying on the work from Cassini"

Computer impact modelling

Impacts into icy bodies can also be investigated using hydrocode modelling. **Tom Davison** (Imperial College London), has undertaken mesoscale modelling of the compaction of water-rich asteroids by low-velocity impacts. This work investigated the shock effect of an impact on granular material with the pore space either filled with void or ice, and the effect of the presence of ice on shock processing of meteoritic materials. The iSALE computer program was used to investigate impacts between two similar bodies made up of olivine ellipsoids randomly oriented and sized, with the voids containing different thickness of water ice to give a varied olivine:ice:void ratio. The results showed that a peak pressure of 10 GPa was reached at a lower velocity for the bodies with the lower ice fraction; this may be a result of the lower porosity or a phase change. This work will continue to investigate similar situations at a range of pressures, and investigate rock:ice:void ratio while keeping the porosity constant.

The meeting then moved on to the final two talks, which investigated water ice on asteroids and the Moon. Asteroid (24) Themis and its putative water ice cap was the topic of **Ben Rozitis** (Open University). Infrared spectra of Themis show absorption features comparable with the shape and position expected of water ice (Campins *et al.* 2010, Rivkin & Emery 2010). This is a surprising observation: small bodies such as Themis do not have atmospheres, and the pressure and temperature is considered too low to prevent any ice, once present, from sublimating. To investigate the stability of the ice, Rozitis applied Rozitis and Green's (2011) advanced thermophysical model to Spitzer and Palomar thermal infrared spectra of Themis, to determine the surface temperature fluctuations. He compared this against sublimation experiments of water ice within a vacuum. The preliminary results suggest that Themis has only one pole region that can support surface water, for a timescale of about 10 000 yr. He also found that this timescale increases to 10^9 yr at subsurface conditions, and confirms the idea that asteroids can contain significant amounts of water as ice. This modelling approach can be used to investigate other main-belt asteroids.

In the final talk of the day, **James Mortimer** (Open University), investigated D/H fractionation during sublimation of water ice at low temperature into a vacuum. This was an apt concluding talk, because this is a process that could have a major effect on all the bodies previous discussed, and one that has the ability to change the composition of water ice. This work formed part of ESA's Prospect programme, which will provide instrumentation for the Russian Luna-27 mission, which aims to land near the lunar south pole and measure the D/H ratio. Before such a mission, laboratory investigations are required to consider how localized heating during sample acquisition would result in fractionation as water ice was lost. Sublimation experiments were therefore undertaken at temperatures between –75 °C and –100 °C, and partial pressures of between 10^{-3} mbar and 10^{-5} mbar. The isotopic composition of the water ice remained constant for proportions up to ~35% of the water ice becoming vapour; sublimated samples were only slightly enriched (±5%) in H and the residues correspondingly enriched in D. Beyond 35% water ice loss, the fractionation trend reversed. But a third of the water ice volume can be lost with no significant fractionation.

Conclusions

This meeting proved to be popular, with an attendance of more than 70 through the day. This showed the widespread interest in this field and the varied implications it has for planetary research in the UK in the future. The broad range of the talks and topics shows that the UK has exciting research covering many aspects of planetary sciences related to these landscapes and bodies. This is a growing field, with forthcoming space missions that aim to focus on icy bodies carrying on the work from Cassini–Huygens, notably ESA's Jupiter Icy Moons Explorer (JUICE), to launch in 2022, and the continuing New Horizons mission, which will encounter another icy body in 2026.

One exciting area of research that was not covered at this meeting is the potential of these bodies for astrobiology. Ice can provide a suitable shield against radiation, meaning that bodies such as Europa and Enceladus with an ice core and a source of water – an essential ingredient of life as we understand it – are potential candidates for finding life via missions such as NASA's Europa Clipper, planned to launch in the 2020s. ●

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