Compositional Mapping of Ganymede with VLT/SPHERE using Markov Chain Monte Carlo Spectral Analysis. O. R. T King[1] and L. N. Fletcher[1], [1]School of Physics and Astronomy, University of Leicester, Leicester, LE1 7RH, UK (ortk1@le.ac.uk, leigh.fletcher@le.ac.uk).

Introduction: The Galilean satellites' surfaces and subsurfaces will be explored by robotic spacecraft in the late 2020s and early 2030s, but significant advances from ground-based astronomical facilities will be possible in the coming decade. Ganymede's surface is composed of regions of brighter young terrain primarily composed of icy material, and older dark terrain which has a higher abundance of silicate rich material [11,16]. Infrared spectra from the Galileo orbiter Near-Infrared Mapping Spectrometer (NIMS) provided high spatial resolution IR spectra of Ganymede but with limited spatial coverage in many locations. In recent years, ground-based adaptive optics observations in the infrared with Keck/OSIRIS and VLT/SINFONI have provided new insights into the distributions of surface materials on the Galilean satellites [2,4,10,11].

Datasets: We acquired near-IR observations of Ganymede with VLT/SPHERE [1] in an observing campaign in 2021. Multiple observations allowed coverage of the majority of Ganymede's surface. Data were taken in IRDIFS_EXT mode, allowing simultaneous imaging with the Integral Field Spectrograph (IFS) and Infrared Differential Imaging Spectrometer (IRDIS) sub-systems of the SPHERE instrument. IFS [5,13] produces image cubes with spectra from 0.95 to 1.65 µm (R~30). It has a high spatial resolution, with a pixel size of 7.46 mas/px, corresponding to ~25 km/px at Jupiter. Accounting for diffraction, this allows features less than 150 km across to be resolved. IRDIS produced simultaneous imaging through two filters, with transmissions centred on 2.11 and 2.25 µm which enables measurement of the strength of water ice absorption around 2 µm. We have also analysed a series of Galileo/NIMS observations with similar spectral and spatial coverage to our SPHERE data. The NIMS detector covering the 0.99 to 1.26µm wavelength range failed early in the Galileo mission at Jupiter, meaning the NIMS coverage of the SPHERE spectral range is limited.

The datasets have been reduced and cleaned to produce mapped spectral cubes of Ganymede's near-IR reflectance spectra. Images are photometrically corrected to remove the variation in brightness towards the edge of the observed disc caused by varying viewing angles and illumination levels of the surface. Our photometric correction uses the Oren-Nayar model, which generalizes the Lambertian model to more accurately represent rough surfaces [15]. This enables regions at large emission angles to be mapped accurately, providing significant improvements over the Lambertian model which overcorrects the brightness towards the edge of the disc. The Oren-Nayar correction allows our mapping to reach emission angles ~70°, higher than previous studies that extend to 50° to 60° [2,7,10].

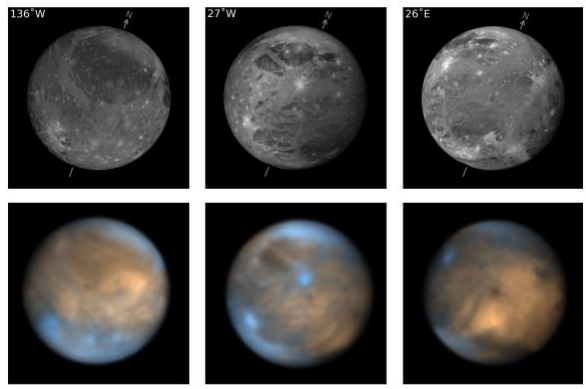

Figure 1: Two-colour images of IRDIS observations (bottom) where orange is 2.11 µm and blue is 2.25 µm, compared to simulated visible light images (top). Water ice has a broad absorption band around 2µm, so the blue areas are icy and orange areas dominated by non-icy species. Large observed features include icy poles and impact craters contrasting with contaminated areas.

Spectral modelling: We analyse the mapped cubes by fitting to laboratory spectra from reference cryogenic libraries. These reference spectra include water ice, sulfuric acid, and hydrated salts [3,8,12]. We have developed an implementation of the Hapke bidirectional reflectance model [9] which we use to model a range of ice grain sizes. We also include 'synthetic' spectrally flat reference spectra to allow modelling of grey material on Ganymede's surface.

Our fitting routine is run for each observed location to produce compositional maps of Ganymede's surface. We treat each observed spectrum as a linear combination of discrete endmembers $E_i(\lambda)$ with respective abundances a_i, where the modelled spectrum is calculated as $M(\lambda) = \sum_i a_i E_i(\lambda)$. Our routine uses Markov Chain Monte Carlo techniques [6] to model an observed spectrum, producing a posterior distribution of fitted abundance values for each endmember, and combinations of different endmembers (Figure 2).

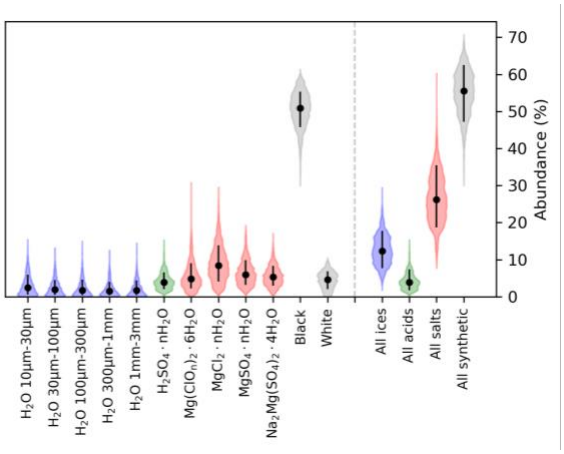

Figure 2: Example fitting results using our Monte Carlo fitting routine on a spectrum from Galileo Regio on Ganymede. The black dots give the best estimate abundance and the lines show the 1-sigma range. The width of the coloured area is representative of the posterior distribution of that endmember's abundance.

The median of each distribution is used as the best estimate abundance for each endmember, and the width of the distribution is used to estimate the uncertainty on that central value. The posterior distributions of combinations of endmembers can likewise be calculated, accounting for correlations in the uncertainties of the summed endmembers. Whilst the uncertainty on a specific endmember's abundance may be large (e.g., a specific ice grain size), the uncertainty of the abundance of a combination of endmembers is often much smaller (e.g., the total abundance of all ice endmembers).

The use of Monte Carlo techniques allows better exploration of the endmember parameter space than a simple linear fit, and the uncertainty estimates allow more detailed understanding of potential detections.

Modelling results show a strong contrast between Ganymede's young bright terrain which has high water ice abundance and old, dark terrain (e.g. Galileo Regio) which is dominated by dark spectrally flat material. The modelled water ice distribution shows a variation in grain size, with larger grains at low latitudes on the trailing hemisphere and smaller grains at higher latitudes (see Figure 3). The spectrally flat material found in Ganymede's dak terrain has a uniformly low albedo (~15%) across Ganymede's surface. Hydrated sulphuric acid appears to be most abundant at high latitudes, consistent with Ganymede's open magnetic field line region.

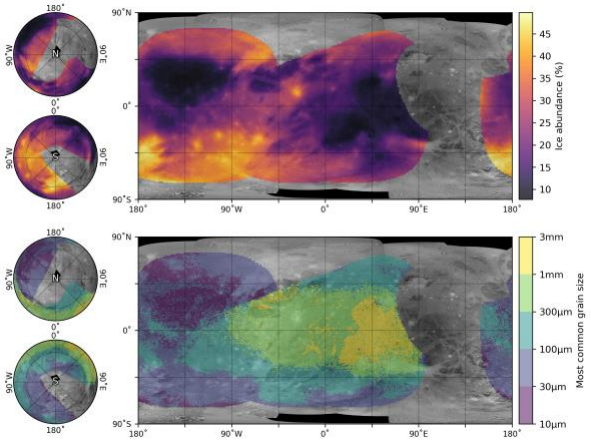

Figure 3: Example fit result showing mapped water ice abundance (top) and most common grain size (bottom) from VLT/SPHERE observations of Ganymede.

Acknowledgments: We would like to thank the Royal Society for supporting this work.

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