PROPERTIES AND COMPOSITION OF GANYMEDE'S SURFACE: UPDATES FROM NEAR-INFRARED GROUND-BASED OBSERVATIONS WITH SINFONI/VLT/ESO.

N. Ligier[1], C. Paranicas[2], J. Carter[3], F. Poulet[3], W.M. Calvin[4], T.A. Nordheim[5], C. Snodgrass[1,6], L. Ferellec[3]. *[1]School of Physical Sciences, The Open University, Milton Keynes MK7 6AA, UK. [2]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723, USA. [3]Institut d'Astrophysique Spatiale, Université Paris-Saclay, 91405 Orsay, France. [4]Geological Sciences & Engineering, University of Nevada, Reno, NV 89557, USA. [5]Jet Propulsion Laboratory, Pasadena, CA 91109, USA. [6]School of Physics and Astronomy, University of Edinburgh, Edinburgh EH8 9YL, UK.*
First author contact: nicolas.ligier@open.ac.uk

Context: Ganymede holds a privileged place in the Solar System in terms of scientific interests. Indeed, some areas on its surface identified as bright grooved terrains (or *sulci*, singular *sulcus*, in Latin for groove) attest to the existence of past endogenic activities such as plate tectonics and cryogenic volcanism [**1**,**2**]. The Galileo mission has showcased Ganymede as a differentiated body composed of three layers [**3**]: a liquid or partially liquid metallic core [**4**], surrounded by a silicate mantle covered by a thick ice shell. Based on a tidal heating model derived from Galileo's data, an ~200 km thick water layer partially or entirely liquid is expected, sandwiched between two layers of ice, at a depth of ~150 km [**5**,**6**]. However, many question remain unanswered. Therefore, ESA and NASA have decided to revisit the Jovian icy moons, and especially Ganymede, during the next decade with two space missions: JUICE (ESA) and Europa Clipper (NASA). In preparation of these missions, and specifically of the near-IR imaging spectrometer MAJIS/JUICE [**7**], a ground-based campaign was led from October 2012 to March 2015 with the imaging spectrometer SINFONI (VLT). Here are presented new results about Ganymede's surface properties and composition from this campaign.

The instrument: SINFONI combines one adaptive optics module and an integral field spectrometer operating in the near-IR with four different gratings: J, H, K and H+K [**8**]. Observations were carried out using the H+K grating. Data wera acquired near opposition to optimize the angular resolution and with the smallest FoV (0.8 × 0.8 arcsec, divided into 64 × 64 pixels) to maximize the spatial resolution. A spectrum, made of 2200 spectels covering the 1.40 – 2.50 µm range is associated to every pixel. Hence, each acquisition results in a 3D-cube (x, y, λ), with dimensions 64 × 64 × 2200. The very high spatial and spectral sampling of SINFONI, coupled with its performing adaptive optics and its excellent S/N ratio, allow to detect and map any spectral absorption that might exist in Ganymede's spectra.

The dataset: The campaign took place from October 2012 to March 2015 during four different nights. This led to angular diameters of Ganymede more than twice larger than the FoV, i.e. from 1.62 to 1.78 arcsec. To cover the entire disk, each observation and each is composed by a mosaic of ten overlapping frames. In addition, cover Ganymede's surface as much as possible, different phases of the moon were observed during the four different nights. Table 1 provides important observational and geographical parameters for the data reduction and map projection.

Acquisition date	Distance to Earth	Strehl ratio	SSP lat./long.
2012/10/30	4.22 A.U.	14.7 ± 0.8	[131ºW, 3ºN]
2012/11/23	4.08 A.U.	37.3 ± 0.5	[255ºW, 3ºN]
2015/02/17	4.36 A.U.	22.0 ± 1.0	[202ºW, 3ºN]
2015/03/08	4.48 A.U.	21.4 ± 1.0	[71ºW, 3ºN]

Table 1. *Main observational and geographical parameters of each observation. [1] SSP: Sub-Solar Point.*

Data reduction: A series of processing steps need to be done to get a single reflectance calibrated 3D-cube for each night of acquisition. All these processing steps are presented in [**9**], except the photometric corrections which are much more complex for Ganymede. Indeed, although a Lambertian model worked well for Europa's H+K data, it quickly appeared that this would not be a good approximation for Ganymede because of its much rougher surface. Another photometric correction was therefore applied, namely the qualitative model of Oren-Nayar, which generalizes the Lambert's law for rough surfaces [**10**]. Here, the roughness parameter, σ, was obtained empirically until getting corrected reflectance 3D-cubes showing no inclination residuals up to inclination angles ~65º (figure 1). Table 2 provides σ for all the observations.

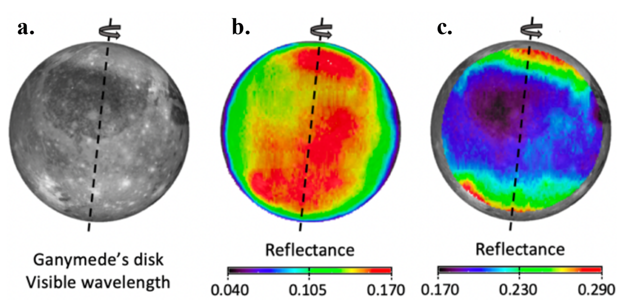

Figure 1. *Ganymede's disk (2012/10/30) in the visible at the time of acquisition (**a.**), SINFONI's uncorrected reflectance at 1.70 µm (**b.**), and SINFONI's Oren-Nayar corrected reflectance (**c.**). Dashed lines represent moon's rotational axis.*

	2012/10/30	2012/11/23	2015/02/17	2015/03/08
σ	21° ± 6°	16° ± 6°	16° ± 6°	19° ± 6°

Table 2. *The roughness parameters for each observation, with error bars determined empirically.*

Data modeling: A linear modeling approach was chosen to model SINFONI's measured spectra. A non-linear, e.g. radiative transfer, approach is generally preferred insofar as it produces better quantitative results and could help to improve the fits further. However, a nonlinear approach requires optical constants for each end-member, which are currently critically lacking at cryogenic temperatures except for H_2O-ice. After numerous tests, Ganymede's surface in SINFONI's H+K range was found to be properly modeled with fourteen end-members belonging to four different mineralogical families: (1) crystalline and amorphous ice (sizes for both phases: 10 µm, 50 µm, 200 µm and 1 mm), (2) a darkening agent, spectrally flat, (3) the sulfuric acid octahydrate and (4) four different salts, precisely two sulfates (hexahydrate and bloedite) and two hydrated chlorinated salts (chloride and chlorate).

Abundance maps and inteerpretations: The fourteen end-members mentioned in the previous section were used to model each pixel's spectrum. Thus, global abundance maps of Ganymede were obtained (figure 2). The H_2O-ice and the sulfuric acid hydrate are distributed quite similarly over the surface. At first order they are strongly dominated by a latitudinal gradient, especially the small grains (10 µm and 50 µm) of H_2O-ice (figure 2a). This gradient is very likely related to the impact of the Jovian magnetosphere insofar as the sharp transition observed in figure 2a around ± 35°N is consistent with Ganymede's magnetosphere open/closed field lines boundaries [**11**,**12**] and with recent models of ion flux impacting the surface [**13**,**14**]. At second order, some light geomorphological correlations are observed for H_2O-ice. An endogenous origin is considered, but a differential grain growth rate due to local differences in terms of albedo and temperature seems more likely so far. Then, the abundance map of the flat darkening agent (figure 2b) is spatially very well anti-correlated to the H_2O-ice. One simple solution to explain this result consists on looking at the main consequence of the surface sputtering: the stronger the sputtering (in Ganymede's case, at the poles), the more eroded the surface and the more particles are ejected [**15**]. These particles will then be redistributed all over Ganymede's surface, but likely mostly locally [**12**,**16**]. The deposit of fresh particles eventually recovers darker particles, overall explaining the distribution observed figure 2b. Two types of salts are required: chlorinated and sulfates. Unlike the other compounds, the spatial distribution of salts (figure 2c) is neither related to the Jovian magnetosphere nor the craters. In addition, they are very mostly detected on sulci, which are the youngest areas of Ganymede's surface [**17**], thus suggesting a potential endogenous origin for these minerals. The process behind the emplacement of these salts will be discussed during the presentation.

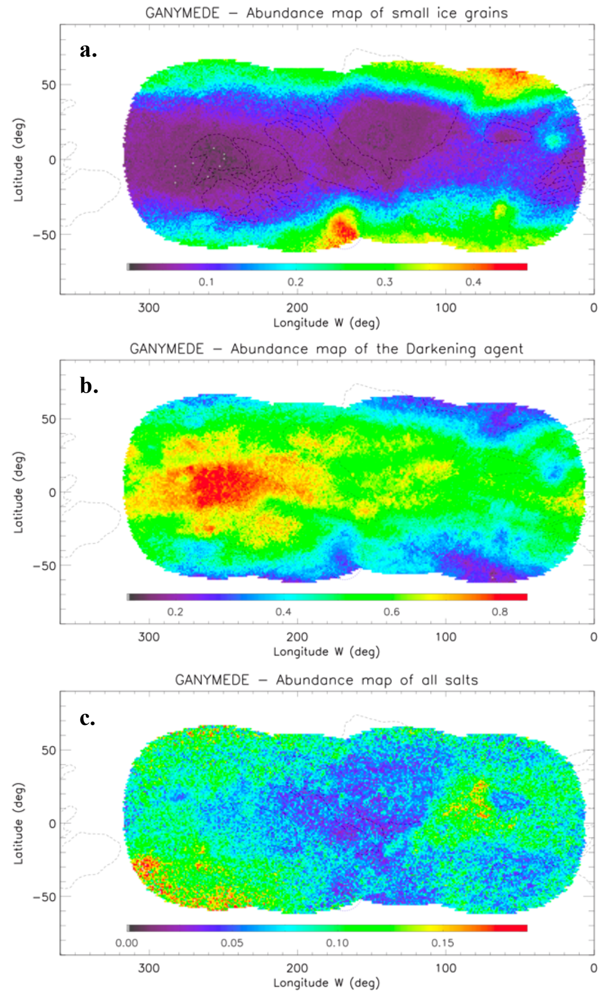

Figure 2. *Abundance maps of compounds used in the modeling. Main geomorphological units are delimited by light grey dots.*

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