Linear polarisation of salty flash-frozen ice particles.

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Introduction: In-situ and telescopic observations of icy moons during the last decades have improved our understanding of these bodies. One of the main features discovered is the production of pristine material at their surfaces by plumes detected on Enceladus[1, 2] and possibly on Europa [3]. In such dynamical environment, the ice particles could be produced by flash-freezing of aqueous solutions expulsed from the subsurface [4, and references therein].

At the University of Bern, the Setup for Production of Icy Planetary Analogues (SPIPA) [5] allows us to produce flash-frozen particles by pulverization of liquid salty solutions into liquid nitrogen. The freezing of the particles is dominated by the Leidenfrost effect [6] which, due to the temperature difference between the liquid nitrogen and the aqueous solution, generates a nitrogen outgassing that makes droplets levitating above it. Therefore, the first seconds of crystallization are made at low (and rapidly decreasing) temperature and induce a complex internal structure of the particles, made of mixed amorphous and crystalline phases.

The characterisation of icy surfaces in total light intensity can be complemented by the analysis of the degree of linear polarisation of the light scattered by atmosphereless bodies, remotely observed from the ground [7]. For many years now, ground-based polarimetric observations have provided a consequent dataset to finely characterize icy surfaces [8, 9] and therefore allow a better preparation for the upcoming space missions Europa Clipper (NASA) and JUICE (ESA). The polarised reflectance is highly sensitive to the morphology of grains (e.g. size, shape, structure) as much as the chemistry (e.g. composition and mixture) [10]. The evolution of polarimetric properties of salty ice particles during warming-up, accompanied with the transition of the amorphous fraction into crystalline, gives insights on the morphology (mostly internal, but also external) of the grains, for the considered salt. To this extent we have measured the evolution of the degree of linear polarisation of salty ices with temperature raising until the eutectic point of the solutions (NaCl, $MgCl_2$, Na_2SO_4 and $MgSO_4$).

POLICES setup: The POLarimeter for ICE Samples has been developed at the University of Bern to measure, among others, the degree of linear polarisation of icy samples [10] and its dependency to phase angle. The experiment is a goniometer with a fixed emergence angle. The incidence angle is defined by the position of the light source, fixed at the end of a rotating motorised arm. Light is either produced by LEDs at four different wavelengths (415, 530, 625 and 810 nm), or in another configuration with a monochromator to select narrow spectral bandpasses. In both cases, depolarisers are used to ensure that the incident light on the sample is depolarised, as the Sun light.

To permit repeatable measurements of icy samples, a hermetic box, painted in black to mitigate stray light, has been added to the setup in order to control the relative humidity in the atmosphere around the sample and prevent the formation of frost. Polarimetric phase curves of icy analogues can be measured with a phase angle ranging from 1.5° to 73° inside the box [10]. We mainly worked with a fixed phase angle to obtain a good time resolution of the evolution of salty-ice particles as their temperature increases. We also started to measure phase curves of flash-frozen salty granular samples.

Sample preparation and measurements: The degree of linear polarisation is maximum at 90° of phase angle [7]. This particular configuration is not reachable with our setup, nevertheless, 60° of phase angle is already a good compromise to record the evolution of linear polarisation. We prepared salty ices made of spherical grains 67±31 µm large [5] from saturated aqueous solutions as well as with lower salt concentrations of $MgSO_4$, NaCl, $MgCl_2$ and Na_2SO_4 (only $MgSO_4$ is presented here).

The ice was inserted into a dedicated sample holder and then placed inside POLICES on a copper plate precooled with liquid nitrogen. The Stokes coefficients, from which the degree of linear polarisation is derived, were continuously measured during the slow warming-up of the sample up to the eutectic point. A Pt-100 sensor inside the ice sample measured continuously the temperature of the ice, a few millimeter below the surface of the sample. The idea behind these experiments was to understand how the polarimetric properties of a flash-frozen sample would evolve during warming-up.

Figure 1 shows the evolution of the degree of linear polarisation of the ice with increasing temperature at a fixed phase angle (60°). Evolutions observed for a given salt seem to be rather independent on the studied wavelengths so far, with only small offsets of the Q/I values (stronger at 415 nm due to a less efficient depolarisation of the incident light). The pristine material is thought to be a mixture of amorphous phase of water and salt, as much as a partially crystallized water ice, in hexagonal and potentially cubic phase [11]. The evolu-

tion with temperature corresponds to the reorganization of the sample, leading to a higher degree of crystallinity of both the ice and the salts. Through this process, the cubic ice initially produced would transition to hexagonal ice and the amorphous arrangement of water and salt would become crystalline. As the water crystallizes, it expels the salt either outside of the particles, coating their surfaces or inside internal cracks within the particle.

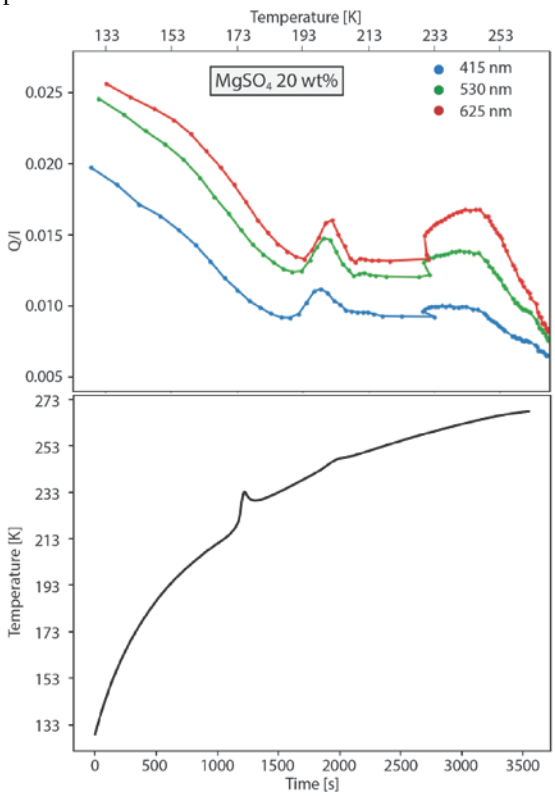

Figure 1 : Evolution of the degree of linear polarisation of salty ices. The measurement of Q/I has been done simultaneously at three wavelengths to explore any potential wavelength dependency.

The first steps of growth of these crystals (water ice and hydrated phases of salts) could be responsible for a minute fraction of Rayleigh scattering, associated to particles that are small in regard to the wavelength. The Q/I values firstly decrease with the warming and then show, at different temperature ranges given the salt, a peak or an increase of the degree of linear polarisation that could be generated by Rayleigh scattering. This mechanism is suspected to be responsible for the peaks of polarisation at 195 K for the $MgSO_4$ (Fig. 1). Figure 2 shows the polarimetric phase curves measured with an incident unpolarised light at 530 nm at different temperatures. The first curves (at the lowest temperatures) exhibit a negative polarisation branch (NPB) with an angle of inversion shifting from 8° to 11°. An interesting point is the presence of oscillations on the phase curve at 175K, which are disappearing rapidly. The oscillations have been previously attributed to the presence of small spherical frost embryos [10]. The presence of frost suggested by the polarimetric phase curves is also a relevant explanations for the decrease of the Q/I values measured at a fixed phase angle (fig. 1).

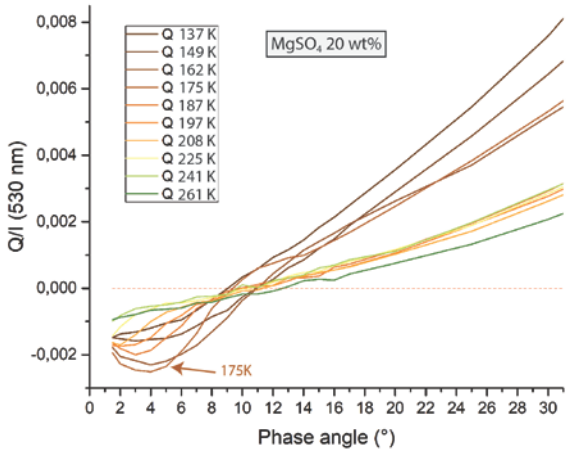

Figure 2: Polarimetric phase curves of flash-frozen icy particles made from a liquid solution of 20 wt% of $MgSO_4$.

Summary and perspectives: The measurements of the degree of linear polarisation have shown their relevance regarding their sensitivity to the grain size and the internal structure of the particles [10]. The new series of measurements proposed in this work will complete the analyses of such brines in total light intensity. We intend to pursue this work with different amount of salts inside the initial brines, as well as other chemical species relevant for the study of icy moons. Once validated, polarisation data will be distributed through the DACE and SSHADE platforms (https://dace.unige.ch/lossySearch/; https://www.sshade.eu/db/bypass).

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