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Correction of Galileos Energetic Particle Detector, EPD, data and the effect on sputtering at Europa

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Abstract

Over the course of its 8-year mission the Energetic Particle Detector, launched in 1989 on the Galileo satellite, took data on the Jovian Particle environment. In the high radiation environment, the EPD composition measurement system became notably decayed; higher mass particles, specifically oxygen and sulphur, read far lower energies and count rates at later epochs in the missions. By considering the non-steady accumulation of damage in the detector, a correction method has been developed. Applying this correction method allows us to reanalyse the data. Specifically, we obtain new estimations on the surface weathering due to sputtering experienced by Europa and the other icy moons. Results of this allow for estimations of surface age relative to surrounding features, achievable using geological techniques.

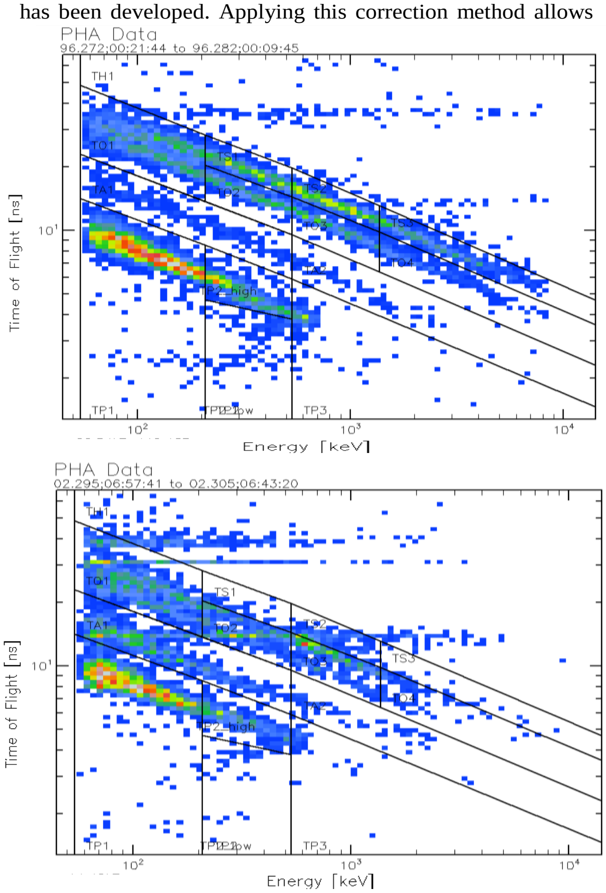

Figure 1: TOP: EPD data beginning on the 29th Sep 1996 shortly after the arrival of Galileo in the Jovian system. BOTTOM: EPD data beginning on the 22nd Oct 2002 nearing the end of the mission lifetime shortly before the demise of Galileo into Jupiter itself

1. Introduction

This paper focuses on the data from the EPD; specifically from the CMS telescope on the top of the instrument. Comparing data from the beginning of the mission to the final data retrieved (Figure 1) there is a clear discrepancy in the loci defining the elements. The uppermost is Sulphur followed by Oxygen beneath it, the faint line in the box labelled TA1 is Helium and the final loci, Protons.

The loci of these elements reveal that the detector is decaying in sensitivity. The amount of energy drop corresponds to the element in question; as a dead layer builds up on the front of the detector, the larger particles lose more energy passing through this layer than lighter elements. This thickening of the dead layer is caused by the radiation impacting onto the detector denaturing the sensitive volume.

By using the comparative count rates from relative locations in the Jovian system at different times, allows the calculation of a value for the decay in terms of counts hitting the detector. Systematically applying this value to the counts registered by the detector brings the values closer to the true values (Figure 2). (Full description of this work is in preparation.)

The correction results are dramatic, with the count rates greatly increased over the whole mission, particularly during the final years. The corrected data matches considerably better with calibration data, both for overall count rates and estimated dead layer thickness. It also fits well with ratioed data taken by Voyager across all elements [1].

2. Implications on Sputtering and Weathering rates at Europa

The key elements involved with the sputtering on the surface of Europa are Sulphur and Oxygen; these are the most effected by the dead layer and thus the correction.

The most common miss-allocation of the particles was a sulphur particle measured by the Oxygen channel. The nature

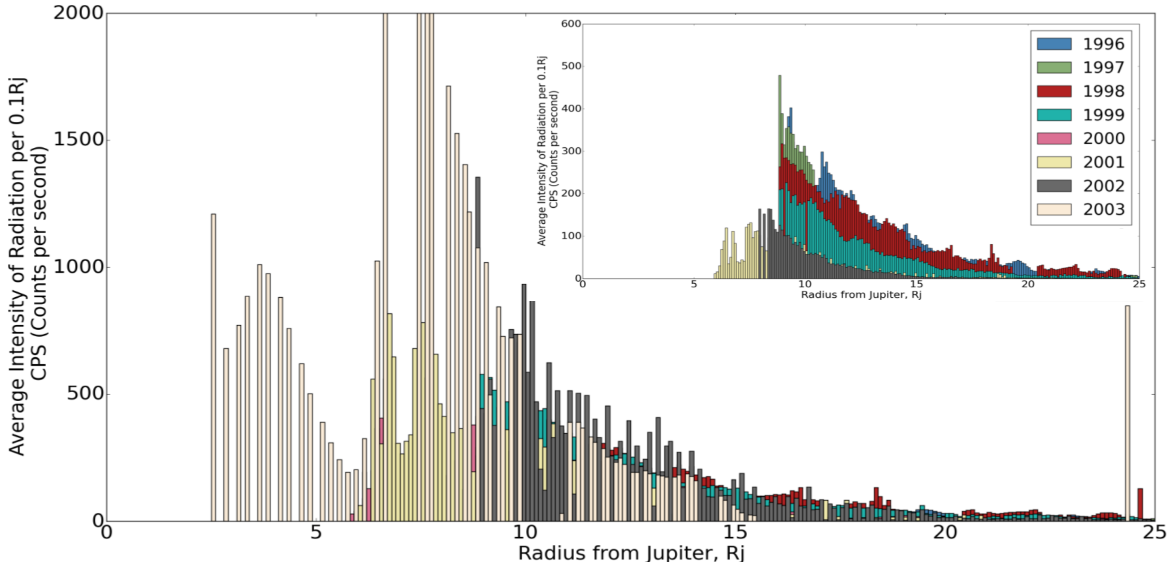

Figure 2: TOP RIGHT OVERLAY: Average count rate against radius for each year of the original TS1 Sulphur channel. MAIN IMAGE: Matching plot of corrected data from TS1 sulphur channel.

of the movement of the particles through the channels means that as the Sulphur channel increases by the correction, then the Oxygen must decrease with the correction. Overall the change is significant, meaning that sputtering on the surface is far more sulphur dominant than originally believed.

The aim of the paper is to determine the new erosion rates on the surface of Europa, and other moons, from using new higher flux rates of the environments energetic particles [2]. From simple estimations, this erosion should be significantly higher giving the possibility of being able to determine an age for the surfaces.

By using geological techniques such as cross cutting on images of the surface such as in Figure 3 it is possible to determine the older features from the newer formations on the surface. As the features accumulate there tends to be a flattening in the formations, the older the feature the less defined it appears to be [3]. By comparing this to well-studied erosion on Earth, wind erosion of ice sheets in the arctic for example, the amount of material removed can be estimated and a period can be established for the age difference in sections of the surface.

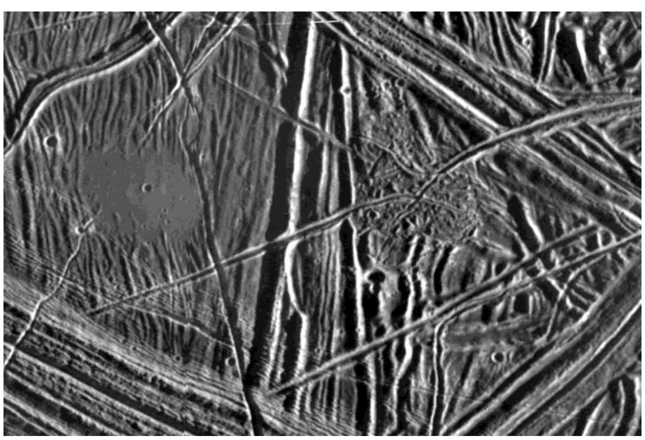

Figure 3: Image of Europa's surface taken by Galileo solid state imaging camera. From https://photojournal.jpl.nasa.gov

3. Summary and Conclusion

The correction of the EPD data is proving to be invaluable in re-evaluating the conditions on the surface of Europa. By calculating the surface erosion, a far more accurate estimate can be put on the age of the surface. Where others previously have only been able to estimate for global coverage, with this technique is may be possible to give dates to specific features and bridge time spans between main formation events.

4. Acknowledgements

The authors would like to thank the EPD analysis team for access to their EPD data files and PHA plotting system software.

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Origin of the water content of Europa : Evidence for pebble accretion ?

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Abstract

Despite the fact that the observed gradient in water content among the Galilean satellites is globally consistent with a formation in a circum-Jovian disk on both sides of the snowline, the mechanisms that led to a low water mass fraction in Europa ($\sim$8%) are not yet understood. Here we show that the water mass fraction of pebbles, as they drift inward, is globally consistent with the current water content of the Galilean system. This opens the possibility that each satellite could have formed through pebble accretion within a delimited region whose boundaries were defined by the position of the snowline.

1. Introduction

The Galilean satellites (Io, Europa, Ganymede and Callisto) are thought to have formed within a disk surrounding Jupiter at the end of its formation. Within this frame, accounting for the bulk composition of Io, which is essentially rocky [5], requires that it fully accreted inside the position of the snowline from water-free material. On the other end, Ganymede and Callisto, both containing $\sim$50% water by mass [5], should have accreted from ice-rich material beyond the position of the snowline. Accounting for Europa's $\sim$8% water by mass is not as straightforward. So far, the only explored scenario is the growth of the protosatellite both inward and outward of the snowline due to either/both disk cooling over time or/and protosatellite migration [1, 2]. Here we study the compositional (i.e., ice-to-rock ratio) and dynamical evolution of solid particles accounting for aerodynamic drag, turbulent diffusion, surface temperature evolution and sublimation of water ice. We show that Europa's water content could be the result of the accretion of partially dehydrated building blocks just inside the snowline rather than its formation within different environments.

2. Method and Results

In our model we track the evolution of individual particles (i.e., lagrangian integration). We integrate the equation of motion together with the equation of surface temperature evolution and ablation rate due to sublimation of water ice for each particle. We also use a Monte-Carlo scheme to account for the turbulent diffusion of the particles [3]. These particles are embedded in a gaseous circum-Jovian disk which is modeled with simple prescriptions giving the gas density and temperature distribution as a function of the mass accretion rate onto Jupiter [4]. When performing our simulations, we release particles of a given size at the midplane of the disk beyond the position of the snowline and let them evolve due to gas drag (inducing inward drift) and turbulent diffusion.
We find that large planetesimals (D$\gtrsim$10 km) are able to retain much more water than smaller ones in a given environment due to the efficient cooling of their surface temperature through water sublimation. Small dust grains (D$\leqslant$1 mm) have very short sublimation timescales and are not able to retain water inside the position of the snowline. The pebbles, solids with typical sizes of 0.01–1 m, are able to transport water inside the position of the snowline as they gradually sublimate while rapidly drifting. This is illustrated on Figure 1 where we present the ice mass fraction of these solids as a function of the distance from Jupiter. Due to the very fast inward motion of the pebbles induced by gas drag, we re-injected the particles that crossed the inner edge of the disk set at 3 R_{Jup} to obtain the curves drawn on the figure.

3. Discussion

Our results suggest that the direct capture of large icy bodies (D$\gtrsim$10 km) on heliocentric orbits towards the circum-Jovian disk could be problematic to form a water-free body such as Io and a Europa with low water content. Instead, the pebbles (0.01–1 m) define three distinct regions in term of composition that

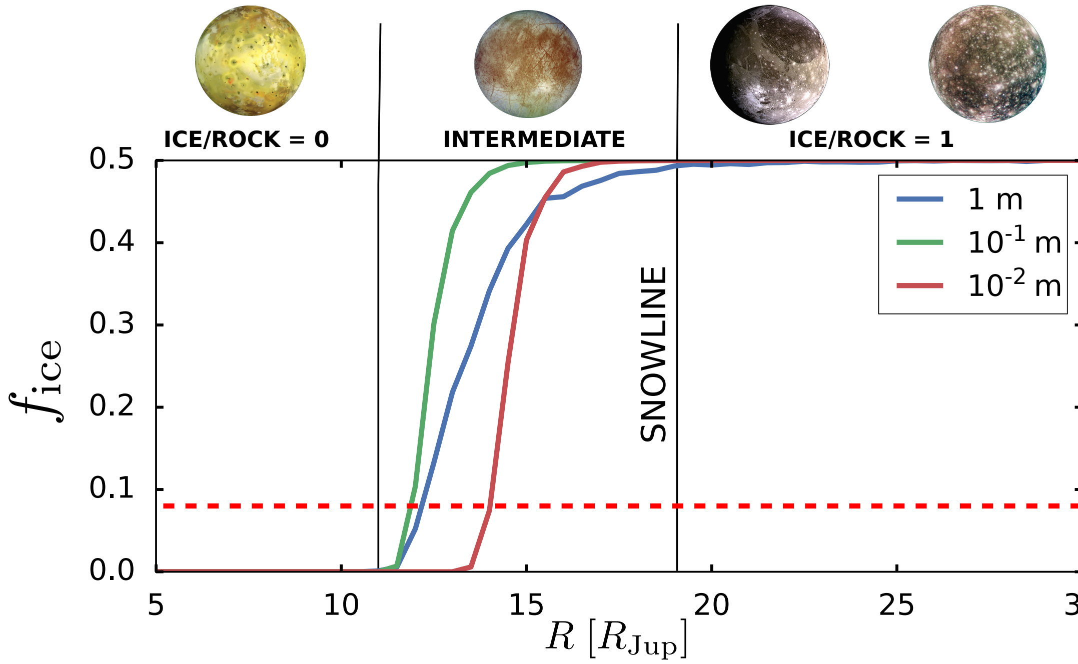

Figure 1: Average water ice mass fraction of solids as a function of radial distance from Jupiter. 10^4 particles of each size have been released in the 25–35 R_{Jup} region. The horizontal dashed line corresponds to Europa's estimated water mass fraction.

are globally consistent with that of the Galilean system. If indeed these solids were the building blocks of the satellites, the formation of Europa could have been restricted to the "intermediate" region just inside the snowline (Fig. 1). There, it would have accreted from partially dehydrated, drifting material, rather than having cross the snowline during its growth. We can note that within this frame, Europa could have formed with any water mass fraction between 0 and 0.5. As migration of the satellites and cooling of the disk likely occured during the formation of the Galilean system, this scenario further implies that the migration of Europa was tied to the evolution of the position of the snowline so that it fully accreted in the intermediate region.

Acknowledgements

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Towards photometry of Europa

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Abstract

Exploring the icy satellites of outter planets is a major step in the search for habitability in our Solar System. This work focuses on Jupiter's icy moon Europa and the images captured by the Long-Range Reconnaissance Imager on-board the New Horizons spacecraft. It is aimed at combining images of the satellite in order to derive photometric reflectance models (i.e. angular response of a surface). It will later be extended to the other two icy Jovian satellites, Ganymede and Callisto and larger data sets.

1. Context

Europa is a prime candidate for habitability in our Solar System. The surface of the moon is the youngest of the Jovian icy satellites. It appears to be continiously renewing by an expanding crust [1]. This activity may be driven by a global water ocean [2] for which more and more evidence seems to be advocating, the latest being the observations of possible water plumes with the Hubble Space Telescope [3].

The JUICE (JUpiter ICy moons Explorer) mission from the European Space Agency (ESA) is to be lauched in 2022 and arrive at the Jovian system in 2030 to study Jupiter and its icy moons for three and a half years. The spcacraft is being designed by Airbus Defence & Space in Toulouse, France, with a very innovative navigation system. Any mission to the outter Solar System is challenging considering local radiative and thermal conditions as well as the distance to the Earth. This new way of navigating aims at making spacecrafts more autonomous and is based on extracting navigation data from on-board image processing [4]. For that algorithm to be successful, the spacecraft needs to have very realistic models of its targets - namely Jupiter's icy moons. This work is starting with combining existing images of Europa to make them comparable as a first step towards deriving reflectance models.

2. Data set

This work is focused on the most recent mission to have encountered the Jovian moons - New Horizons. On its way to Pluto, the spacecraft spent three months observing Jupiter and its moons in 2007 with the LORRI (LOng-Range Reconnaissance Imager) camera [5]. Combining all the images captured during the Jupiter phase of the mission, the whole surface of Europa is accounted for.

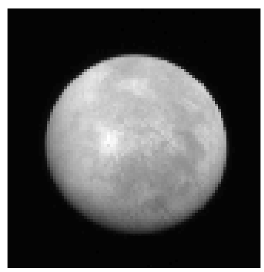

Figure 1: Example of a LORRI observation

By comparing New Horizons images of Europa to simulations based on the available geometry and attitude meta-data from SPICE kernels, it was found that imprecisions in meta-data [4] resulted in considerable errors when associating pixels to their coordinates on the moon. The first step is therefore to improve the meta-data as much as possible to have a coherent data set.

3. Method

Images are compared two by two to ensure that when looking at a common part of the moon, two images are matching. By considering one image as the reference, each pixel of the second image needs to be projected onto the moon to estimate its coordinates (Fig. 2).

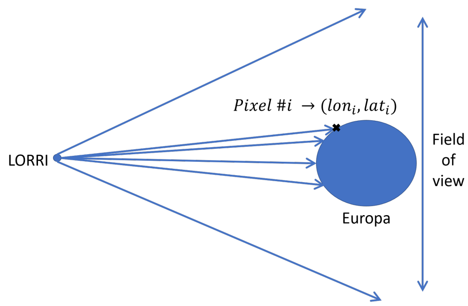

Figure 2: Schematic view of projecting pixels on moon

Step by step the global map of the moon will be reconstructed. Moreover, since all images are taken with different geometries (incidence, emergence and phase angles), it will be possible to determine the photometric behavior of the moon.

4. Conclusion

Next steps will include extracting information from the reflectance variations at the surface and the global photometry. This will also be an opportunity to estimate the structure of the moon's surface - for instance its micro-texture - as it has been done on Mars [6].

In addition, the available data set of past missions is quite rich. Galileo studied the Jovian system for seven years between 1995 and 2002. Cassini also briefly captured images of the icy moons in 2001. We plan to extend our work to these data sets. The same methodology should also be applied to the other two Jovian icy moons: Ganymede and Callisto.

Acknowledgements

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The Europa Clipper Mission: Exploring The Habitability Of A Unique Icy World

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1. Introduction

A key driver of planetary exploration is to understand the processes that lead to potential habitability across the solar system. In the forefront of this objective is evaluating the astrobiological potential of the icy outer planet satellites. It is in this context that a mission to Europa is currently being formulated.

2. Mission Goal, Objectives, and Investigations

The overarching science goal of the Europa mission is to explore Europa to investigate its habitability. Following from this goal are three Mission Objectives (bold roman numerals), from each of which flow several Mission Investigations (numbered items), as listed below. Also listed (abbreviations) are each of the instruments, plus Gravity and Radiation science, that synergistically address these Investigations and Objectives, which are defined and discussed in more detail in the next section. Folded into these three objectives is the desire to search for and characterize any current activity, notably plumes and thermal anomalies.

I. Ice Shell & Ocean – Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange.

1. Characterize the distribution of any shallow subsurface water and the structure of the icy shell *(EIS, REASON)*;
2. Determine ocean salinity and thickness *(ICEMAG, MISE, PIMS, SUDA)*;
3. Constrain the regional and global thickness, heat-flow, and dynamics of the ice shell *(E-THEMIS, EIS, Gravity, ICEMAG, PIMS, REASON)*;
4. Investigate processes governing material exchange among the ocean, ice shell, surface, and atmosphere *(EIS, ICEMAG, MASPEX, MISE, REASON, SUDA)*.

II. Composition – Understand the habitability of Europa's ocean through composition and chemistry.

1. Characterize the composition and chemistry of endogenic materials on the surface and in the atmosphere, including potential plumes *(EIS, Europa-UVS, ICEMAG, MASPEX, MISE, PIMS, REASON, SUDA)*;
2. Determine the role of the radiation and plasma environment in creating and processing the atmosphere and surface materials *(EIS, Europa-UVS, MASPEX, MISE, PIMS, Radiation, REASON, SUDA)*;
3. Characterize the chemical and compositional pathways in the ocean *(EIS, ICEMAG, MASPEX, MISE, SUDA)*.

III. Geology – Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities.

1. Determine sites of most recent geological activity, including potential plumes, and characterize localities of high science interest and potential future landing sites *(E-THEMIS, EIS, Europa-UVS, MASPEX, MISE, PIMS, Radiation, REASON, SUDA)*;
2. Determine the formation and three-dimensional characteristics of magmatic, tectonic, and impact landforms *(EIS, REASON)*;
3. Investigate processes of erosion and deposition and their effects on the physical properties of the surface *(E-THEMIS, EIS, Europa-UVS, PIMS, Radiation, REASON, SUDA)*.

3. Exploring Europa Through Synergistic Investigation

To address the science questions of the Europa mission, NASA selected a scientific payload comprised of nine instruments. This payload includes five remote-sensing instruments that observe the wavelength range from ultraviolet through radar, and four *in situ* instruments that measure fields and particles.

Europa Ultraviolet Spectrograph (Europa-UVS). Operating at ultraviolet wavelengths, Europa-UVS will measure the composition and chemistry and the structure and variability of Europa's tenuous atmosphere. In addition, Europa-UVS will enable characterization of the plasma environment and the search for and characterization of the distribution, structure, composition, and variability of any active plumes. Europa-UVS data can constrain surface composition and microphysics and relationships to endogenic and exogenic processes.

Europa Imaging System (EIS). Composed of a narrow- and wide-angle camera with stereo and color imaging capability, EIS can map Europa globally at 100 m resolution and image almost any point on the surface at better than 20 m resolution, providing constraints on the formation of surface features. Very high-resolution imaging addresses small-scale regolith processes and can characterize sites amenable for a future lander. Distant imaging would search for active plumes and provide a means to characterize the ice shell through modeling of the limb shape.

Mapping Imaging Spectrometer for Europa (MISE). Operating in the 0.8–5.0 μm wavelength range, MISE data can be used to assess the habitability of Europa's ocean through examination of the inventory and distribution of surface compounds, including any biologically relevant deposits. MISE data can be used to identify and map the distributions of organics, salts, acid hydrates, water ice phases, altered silicates, radiolytic compounds, and warm thermal anomalies at global, regional, and local scales on Europa.

Europa Thermal Imaging System (E-THEMIS). The E-THEMIS investigation permits detection and characterization of thermal anomalies that may indicate recent activity. Thermal inertia information derived from E-THEMIS measurements can be used to characterize regolith particle size, block abundance, and subsurface layering. This investigation can also aid characterization of any active plumes.

Radar for Europa Assessment and Sounding: Ocean to Near-surface (REASON). REASON data will permit mapping of Europa's vertical crustal structure and the search for subsurface water. They can also be used to study the distribution of shallow subsurface water and to search for the deeper ice-ocean interface and to provide insight into material exchange among the ocean, ice shell, surface, and atmosphere. Solid body geophysical measurements can constrain the amplitude and phase of the tides. Derived dielectric and other physical properties support characterization of the scientific value and hazards of sites for a potential future lander.

Interior Characterization of Europa using Magnetometry (ICEMAG). ICEMAG can measure magnetic fields to infer magnetic induction at multiple frequencies. This, in turn, would permit the location, thickness, and salinity of Europa's ocean to be estimated. In addition, the data can be used to identify sources and losses of Europa's atmosphere, coupling of Europa to Jupiter's ionosphere, and coupling of any plumes to flowing plasma.

Plasma Instrument for Magnetic Sounding (PIMS). PIMS data can be used to identify plasma contributions to Europa's magnetic field and to understand mechanisms of weathering and release of material from Europa's surface into the atmosphere. PIMS data can facilitate an understanding of how Europa influences its local space environment and Jupiter's magnetosphere.

MAss Spectrometer for Planetary Exploration /Europa (MASPEX). MASPEX can perform *in situ* analysis of neutral gases to identify major volatiles and key organic compounds in Europa's exosphere and possible plumes, and their association with geological features. MASPEX data can be used to derive the relative abundances of key compounds, to constrain the chemical conditions and biological suitability of Europa's ocean including isotopologues, radiolysis products, and organic molecules.

SUrface Dust Analyzer (SUDA). The SUDA investigation can map surface composition by direct analysis of particles ejected by micrometeoroid impacts. SUDA data can be used to characterize the alteration of Europa's surface via exogenous dust and to determine the composition of particles in active plumes to determine ocean properties.

In addition, gravity science can be achieved via the spacecraft's telecommunication system in combination with radar altimetry. Moreover, the spacecraft's planned radiation monitoring system could provide valuable scientific data. Working together, the Europa mission's robust investigation suite can be used to test hypotheses and enable discoveries relevant to the interior, composition, and geology of Europa, thereby addressing the potential habitability of this intriguing ocean world.

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Ice particle size variations and candidate non-ice materials on Ganymede and Callisto

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1. Introduction

Band depth ratios (*BDR*s) of the major H_2O-ice absorptions in the spectra of the Jovian satellites Ganymede and Callisto acquired by the NIMS spectrometer onboard the Galileo spacecraft [1] have been found to be semi-quantitative indicators of changes in the ice particle sizes across its surface allowing their detailed mapping across the satellites' surfaces without extensive modeling [2]. Based on the achieved results, processes responsible for these variations as well as the implications for the nature and composition of the dark non-ice materials on both satellites have been investigated.

2. Ice particle size variations

Intriguingly, the general H_2O-ice particle size variations show almost no correlation with the surface geology but change continuously with geographic latitude on both satellites. On Ganymede, sizes reach from 1 µm near the poles to > 100 µm up to 1 mm near the equator [2, 3]. Smallest particles occur at latitudes higher than ±30° where the closed magnetic field lines of Ganymede's magnetic field change into open ones and Ganymede's polar caps become apparent. On Callisto, which does not exhibit an intrinsic magnetic field, however, *BDR*s show a similar trend. Ice particles appear slightly larger at low and mid latitude than observed on Ganymede, whereas the ratio values converge toward the poles indicating similarly small ice particle sizes.

Similar trends in the particle size variations on Callisto as well as on Ganymede imply that these variations are caused by similar surface processes. The formation of Ganymede's polar caps has often been attributed to brightening effects due to sputtering of ice by plasma bombardment with local and regional redeposition as finer grained ice [4, 5]. Our measurements rather point to a continuous decreasing of ice particle sizes toward the poles on both satellites. This smooth latitudinal trend may be related to the surface temperatures and possible thermal migration of water vapor to higher latitudes [6] and grain welding at lower latitudes. Maximum temperatures during the day reach 150 K and 165 K near the equator of Ganymede and Callisto [7, 8], respectively. At these temperatures, ice sublimation and crystal growth [9], whose rates are exponentially dependent on temperature, will be processes that occur rapidly compared to impact processes. In contrast, polar temperatures do not exceed 80 ± 5 K [10, 7] and ice will be immobile. Larger particles in the equatorial region of Callisto than on Ganymede could be explained due to the slight higher maximum temperature but also a longer Callistoan day (Callisto: ~ 17 Earth days; Ganymede: ~ 7 Earth days) [8].

3. Implications for the dark non-icy material

The specific composition of Ganymede's and Callisto's non-ice material is still not fully solved. However, it is not expected that the observed relationship between the H_2O-ice absorptions occurs for every non-ice material and thus might help to restrict the variety of considered materials such as carbon-rich materials, phyllosilicates and H_2O-bearing salts [7, 8, 11, 12].

Areal mixtures of H_2O ice with possible dark non-ice candidates such as carbon-rich material, hydroxylated and hydrated phyllosilicates [7, 8] have been calculated depending on different abundance and H_2O-ice particle sizes. The relationship between the H_2O-ice particle sizes and the *BDR*s is valid for most materials if the amount in the mixture does not exceed 10%. Best results across the full range of percentage could be achieved for carbon-rich material and hydroxylated phyllosilicates as expected in carbonaceous chondrites [11]. In contrast, significant amounts of hydrated material as identified on Ganymede and Europa [12] significantly changes the *BDR*s and cannot fully explain the global trend.

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Alcali in Europa's exosphere: an endogenous scenario

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Abstract

An endogenous scenario is developed that follows the alkali metals from their washing out of the rocky kernel of Europa by the internal ocean in the early times of the satellite formation. During the cooling period, the ice crust formed at the surface of the ocean and trapped the alkali allowing them to migrate to the surface and be ejected in the exosphere. This scenario is supported by "first principle" numerical simulations showing the trapping and progressive neutralization of the initial ions in the ice matrix.

1. Introduction

Because Europa is believed to hide a deep ocean beneath its icy shell, the question that it could have seen the development of an early form of life is actually of real concern. The detection of sodium and potassium in the exosphere [1] might be a hint of the emergence of primitive cells because these alkali metals are well-known to be associated with the opening and closing of the activation gates of the Na^+, K^+, ionic channels through cellular membranes [2-4].

It has been proposed that these metals could have either exogenous or endogenous origin:

- exogenous, if inherited from contamination from the intense volcanism of Io nearby and/or the implantation of these elements due to meteoritic bombardment. However, these scenarios do not account for the Na/K ratio of ~25 measured in Europa's exosphere,
- endogenous, if produced by a chemical scenario starting deep in the core of this Jovian moon, and delivered to the surface via the upwelling of ices formed in contact with the hidden ocean.

2. Computational background

The approach used is based on periodic DFT whose implementation relying on plane waves expansions removes the artifacts created by limited clusters and finite basis sets. The PBE+D2 functional is employed (including Grimme correction [5]) for a better description of long-range interactions. The Vienna Ab-initio Simulation Package (VASP) is used in all calculations [6]. How the electronic charge of Na and K vary in relation with the ice environment have been addressed by means of a topological analysis of the electron localization function recently extended to periodic systems [7].

3. The way out to the exosphere

In a preceding study of the origin of neutral Na in cometary tails [8], it was shown that, whatever the disk temperature of the protosolar nebula, all the sodium is contained in refractory materials below 800K (here we assume this to be true also for potassium).

The formation of an internal ocean following a progressive cooling created the conditions favorable to the washing of the rocky kernel that resulted in the transfer of Na and K to the surrounding water in the form of positive ions in abundances related to their relative solubility.

Due to the lack of in-situ data, we turned to plausible similar situations on Earth, namely those that can be found in geothermal fields. Extensive studies have been carried out in Iceland to determine the hardness of water as a function of temperature in view of possible exploitation of the Bakki geothermal field [9]. These investigations show that the molalities (mole/l) present very little changes for water/rock ratios between 10^3 and 10^6. No saturation being implied, we took the molalities of 0.750 and 0.025

mole/l obtained for a water/rock ratio of 10^6 at 393K for Na and K, respectively.

Following Europa's cooling, an ice shield formed on the ocean surface whose thickness increased with time imprisoning sodium and potassium (together with other solutes). The migration of the metals from deep inside to the top ice layers can then proceed via convection/diapirism [10].

The crucial point at this stage is the metal ability to stabilize, E_{Stab}, within the icy structure. It is define as:

$$E_{Stab} = \left(E_{Ice} + E_{Metal}\right) - E$$

where E_{Metal} is the energy of the metal, E_{Ice} is the energy of the pristine ice bulk and E the total energy of the [Ice bulk+ Metal] system in which all entities are optimized in isolation.

Typical situations in the migration of the metal toward the surface are quantified in Table 1.

Table 1: Stabilization energies (eV) and atomic charges (electron unit)

Environment	Na E_{stab} (q)	K E_{stab} (q)
Inclusion in the bulk	0.1 (0.9)	0.2 (0.9)
Substitution: 1 H_2O hole	1.0 (0.8)	0.9 (0.8)
Substitution: 4 H_2O hole	1.4 (0.6)	1.6 (0.8)
Adsorption (surface)	0.1 (0.2)	0.2 (0.1)

The inclusion in the bulk means that Na, K, would stay ionic trying to force their way in the ice lattice, which appears difficult in view of the poor energy stabilization. In holes (substitution) corresponding to the removal/destruction of 2 or 4 H_2O molecules, the alkali metals lose part of their positive charge and are stabilized by an energy that increases with the size of the cavity in which they are trapped (porous ice). In the end they reach the ice surface where they are neutral (q~0.2 e) and weakly adsorbed (0.1-0.2 eV), ready to be ejected in the exosphere by any external energy (irradiation or collisional sputtering).

4. Summary and Conclusions

In a purely chemical scenario we show that Na and K can be washed out of the solid core of Europa, transferred into the internal ocean, possibly embedded in the ice shell and pushed up to the surface by solid convection where they remain as neutral atoms until they are ejected in the exosphere. Since there is no noticeable difference between the stabilities of Na and K in the ice, the initial relative abundances in the ocean water should be the discriminating factor and not the cosmic abundances. It lets anticipate an abundance of Na released in the gas phase greater than that of K by more than an order of magnitude. The ratio of the molalities being ~30, gives an estimation close to that found in the observations.

A similar scenario may be anticipated for other volatiles provided they can be trapped inside cavities in the forming ice of porous nature.

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Biomarker Production and Preservation on Europa

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Abstract

Here, I address the production of biomarkers, the evolutionary path such a signal may undergo, and what considerations this yields for the selection of landing sites, sampling techniques, and sample analyses that march us towards a definitive detection of life.

1. Introduction

Landing on the surface of Europa, and one day exploring its deeper subsurface, are lauded goals in the exploration of the solar system. For now it seems, we may be confined to the surface and shallow subsurface, where both endogenic and exogenic factors exists that could complicate our picture of the habitability of Europa and whether life itself can be detected. In order to assure high science return from a future landed mission, we must carefully consider what the nature of any material sampled may have been. A number of authors have discussed related topics in the literature, including considerations of surface age and roughness [1], radiation and chemical processing [2] and the chemistry of the ocean [3,4], etc.

2. A Working Model

It is difficult to confidently define a model for Europa (or other ocean worlds) from which we might hope to derive landing site selection and sampling techniques, given that most of our experience in searching for life is derived from a very different perspective—that of a terrestrial planet. For Mars, such a perspective is helpful. We understand sedimentology, hydrology, tectonics, wind erosion and other factors that effect the history of the planet that we experience. However, at least at the surface, the habitability of the systems we study are largely depositional, or at least constrained to the outer veneer of the planet. On Europa, the scenario is quite the opposite, where the surface is passively experiencing communications from the putative habitable niches below that extend throughout the ice shell and ocean and sea floor. Europa, except in some limited cases, may not be "depositional."

In this work, I approach Europa based on the many hypotheses we have that govern the generation or sup-port of life, the processes that occur within the sea-floor, ocean, and ice and exchange between them, and the geologic hypotheses for the formation of its various surfaces to establish, for each case, what journey through the planet the biomarker, might take to arrive, if possible, at the surface where it is accessible to near-term landed mission.

Biomarker production: I first consider the nature of the environment, i.e. at the sea floor interface, the ocean, or ocean-ice interface, in order to establish what the likely "biomarker" could be for that system.

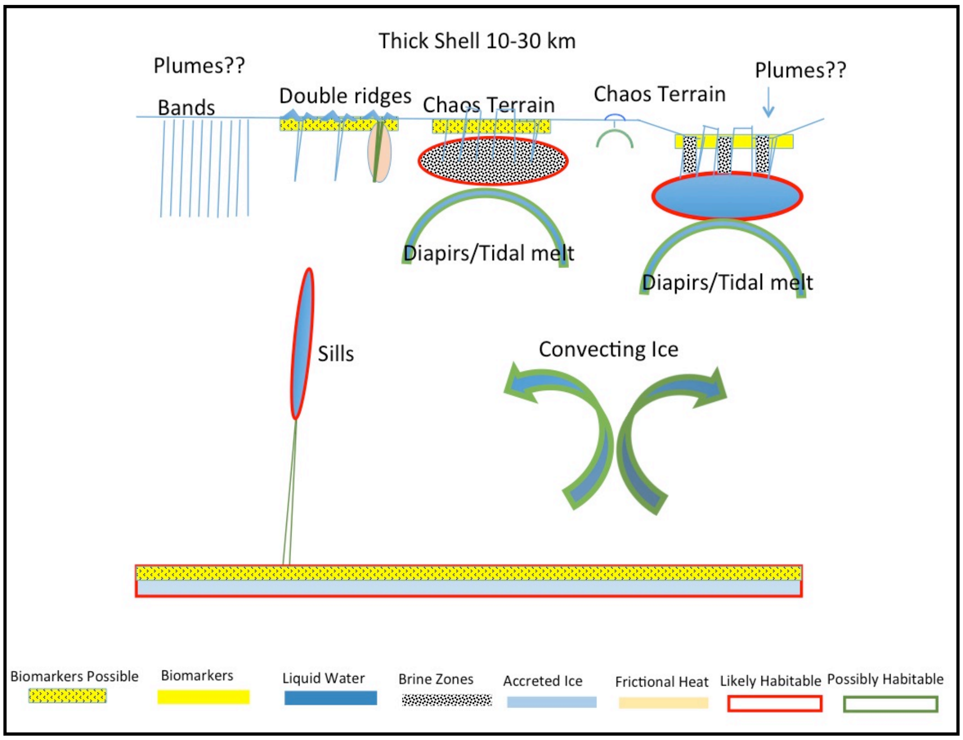
Biomarker pathways: Then I trace its path through the system: any downwelling through the subsurface, mixing through the ocean, and pathways to the surface. And while looking for surface deposits from plumes or emplaced material is part of the story, it is potentially dangerous to trust our intuition that the surface will be simple or easy to interpret without a three dimensional context.

Biomarker concentration or destruction: Importantly, many models exist for the production of Europa's surface and subsurface geology that could affect the integrity of a putative biomarker. Often we modulate such considerations as a function of the time-scales over which the geologic process occurs, however such processes will vary in terms of transportation efficiency, and the processing of the ice and water that is incorporated into the ice shell. Thus I seek to provide simple constraints and considerations for leading mechanisms (i.e. diapirism, convection, subsumption).

3. Implications

The goal of this project is to construct a simple model through which to consider the context for sampled material that will provide us with the ability to identify limitations in our intuition, understanding of the Europan system, our current hypotheses and data, and provide a road map for developing both areas for new research and identifying technology gaps that we must overcome before we can confidently select a landing site or analyze a sample from the near surface of Europa. There has been great progress in modernizing our ideas of how Europa works: its surface dynamics [5,6], ocean dynamics [7], and chemistry [4]. These new advancements improve the fidelity of the efforts described here. I will also comment on synergies between the upcoming JUICE and Europa Clipper missions, any putative landed mission, and how these missions could provide invaluable data that allows us to get beneath Europa's icy skin in relatively short order.

Figure 1: Regions of likely biomarker production, entrainment, and processing for a thick ice shell.



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Exploration of Jupiter's atmosphere and magnetosphere with the European Jupiter Icy Moon Explorer (JUICE)

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Abstract

JUICE - JUpiter ICy moons Explorer - is the first large mission in ESA's Cosmic Vision 2015-2025 programme. The mission was selected in May 2012 and adopted in November 2014. The implementation phase started in July 2015. Planned for launch in June 2022 and arrival at Jupiter in October 2029, it will spend at least three years making detailed observations of Jupiter and three of its largest moons, Ganymede, Callisto and Europa. JUICE will then orbit Ganymede for almost a year.

JUICE will perform a varied and extensive orbital tour with access to high latitudes to provide a comprehensive study of the unique environmental conditions at Jupiter's poles.

The overarching theme for JUICE is: *The emergence of habitable worlds around gas giants*. JUICE will also perform a multidisciplinary investigation of the Jupiter as an archetype for gas giants. In this paper, we will present the science objectives and key measurements performed by the instrument suite, relevant to the study of the atmosphere and magnetosphere of Jupiter. We will also present the first steps of the science implementation, as performed by the ESA Working Groups and Science Working Team.

Jupiter Atmospheric Science

JUICE will study Jupiter's atmosphere as a complex, coupled system from the dynamic weather layer to the upper thermosphere. It will study the variability of Jovian climatology, dynamics, winds, gaseous composition and cloud structure.

The instruments of the remote sensing package will conduct the required measurements. It consists of imaging (JANUS) and spectral-imaging capabilities from the UV to the sub-mm wavelengths (UVS, MAJIS, SWI).

Jupiter Magnetospheric Science

JUICE will investigate the 3D properties of the magnetodisc, and will study the coupling processes within the magnetosphere, ionosphere and thermosphere.

The instruments of the in situ package will perform the key measurements relevant to these objectives. It comprises a suite to study plasma and neutral gas environments (PEP) with remote sensing capabilities via energetic neutrals, a magnetometer (J-MAG) and a radio and plasma wave instrument (RPWI).

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JUICE: A European mission to explore the emergence of habitable worlds around gas giants

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Abstract

JUICE - JUpiter ICy moons Explorer - is the first large mission in the ESA Cosmic Vision 2015-2025 programme. The mission was selected in May 2012 and adopted in November 2014. The implementation phase started in July 2015, following the selection of the prime industrial contractor, Airbus Defense and Space (Toulouse, France). Due to launch in June 2022 and arrival at Jupiter in October 2029, it will spend at least three ½ years making detailed observations of Jupiter and three of its largest moons, Ganymede, Callisto and Europa.

1. Science Objectives

The focus of JUICE is to characterise the conditions that might have led to the emergence of habitable environments among the Jovian icy satellites, with special emphasis on the three worlds, Ganymede, Europa, and Callisto, likely hosting internal oceans [1,2]. Ganymede, the largest moon in the Solar System, is identified as a high-priority target because it provides a unique and natural laboratory for analysis of the nature, evolution and potential habitability of icy worlds and waterworlds in general, but also because of the role it plays within the system of Galilean satellites, and its special magnetic and plasma interactions with the surrounding Jovian environment. The mission also focuses on characterising the diversity of coupling processes and exchanges in the Jupiter system that are responsible for the changes in surface and space environments at Ganymede, Europa and Callisto, from short-term to geological time scales. Focused studies of Jupiter's atmosphere and magnetosphere, and their interaction with the Galilean satellites will further enhance our understanding of the evolution and dynamics of the Jovian system. The overarching theme for JUICE is: The emergence of habitable worlds around gas giants. At Ganymede, the mission will characterise in detail the ocean layers; provide topographical, geological and compositional mapping of the surface; study the physical properties of the icy crusts; characterise the internal mass distribution, investigate the exosphere; study Ganymede's intrinsic magnetic field and its interactions with the Jovian magnetosphere. For Europa, the focus will be on the surface composition, understanding the formation of surface features and subsurface sounding of the icy crust over recently active regions. Callisto will be explored as a witness of the early solar system trying to also elucidate the mystery of its internal structure. JUICE will perform a multidisciplinary investigation of the Jupiter system as an archetype for gas giants. The Jovian atmosphere will be studied from the cloud tops to the thermosphere. The focus in Jupiter's magnetosphere will include an investigation of the three dimensional properties of the magnetodisc and in-depth study of the coupling processes within the magnetosphere, ionosphere and thermosphere. JUICE will study the moons' interactions with the magnetosphere, gravitational coupling and long-term tidal evolution of the Galilean satellites.

2. The Payload

The JUICE payload consists of 10 state-of-the-art instruments plus one experiment that uses the spacecraft telecommunication system with ground-based instruments. This payload is capable of addressing all of the mission's science goals [1,2], from in situ measurements of the plasma environment, to remote observations of the surface and interior of the three icy moons, Ganymede, Europa and Callisto, and of Jupiter's atmosphere. A remote sensing package includes imaging (JANUS) and spectral-imaging capabilities from the ultraviolet to the sub-millimetre wavelengths (MAJIS, UVS, SWI). A geophysical package consists of a laser altimeter (GALA) and a radar sounder (RIME) for exploring the surface and subsurface of the moons, and a radio science experiment (3GM) to probe the atmospheres of Jupiter and its satellites and to perform measurements of the gravity fields. An in situ package comprises a powerful suite to study plasma and neutral gas environments (PEP) with remote sensing capabilities via energetic neutrals, a magnetometer (J-MAG) and a radio and plasma wave instrument (RPWI), including electric fields sensors and a Langmuir probe. An experiment (PRIDE) using ground-based Very Long Baseline Interferometry (VLBI) will support precise determination of the spacecraft state vector with the focus at improving the ephemeris of the Jovian system.

3. The mission profile

The mission is due to launch from Kourou with an Ariane 5 ECA. The baseline launch is 1st of June 2022, which is in the middle of a 20 days launch window. There are backup launch slots two or three times per year. The interplanetary transfer sequence relies on gravity assist with Venus, the Earth and Mars. The Jupiter orbit insertion will be performed in October 2029. An initial Ganymede swing-by is performed just before the capture manoeuvre. The tour of the Jupiter system, as currently designed, starts with a series of three Ganymede swing-bys. The spacecraft is transferred to Callisto to initiate the Europa science phase, one year after the Jupiter insertion. This phase is composed of two fly-bys, separated by 15 days, with closest approach at 400 km altitude. The next phase is a 200-day period characterised by an excursion at moderate inclinations, in order to investigate regions of the Jupiter environment away from the equatorial plane. A series of resonant transfers with Callisto raise the inclination with respect to Jupiter’s equator to a maximum value of 28 deg. The spacecraft is then transferred from Callisto to Ganymede with a series of Callisto and Ganymede flybys, followed by a gravitational capture with the moon. The science phase around Ganymede is decomposed into a first elliptic subphase, a circular orbit at 5000 km altitude followed by a second elliptic subphase, and then a circular phase at 500 km altitude. The total duration of the Ganymede orbital phase is about nine months, the end of mission being planned in September 2033. The spacecraft will eventually impact the surface.

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Are there signatures of active Europa plumes in Galileo in-situ data?

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Abstract

Hubble Space Telescope observations made during recent years suggest that recurring water vapour plumes originating from Europa's surface exist, though they do not conclusively prove their existence [1, 2, 3]. Taking samples of these plumes in-situ from a flyby mission could allow for the study of Europa's potentially habitable ocean [4].

Indisputable (in-situ) observations of these plumes have not been reported yet. However, it may be possible that the NASA Galileo mission encountered these plumes. This mission was active in the Jupiter system from 1995 to 2003 and made several Europa flybys. It has been suggested that the high plasma densities and anomalous magnetic fields measured during the E12 flyby could be connected to active plumes [5, 6]. No new opportunity to study these plumes in-situ will arise before the early 2030's when ESA's JUICE mission or NASA's Europa Clipper will arrive.

We present an overview of in-situ data obtained by the Galileo spacecraft during the Europa flybys. The data is compared in the context of the search for signs of active plumes. Focus is in particular on the data obtained with the plasma instruments PLS (low energy ions and electrons), EPD (high energy ions and electrons) and MAG (magnetic fields).

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Water generation and transport through the high-pressure ice layers of Titan and Ganymede

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Abstract

We investigate the generation and transport of water through the high-pressure (HP) ice layers of Ganymede and Titan using a numerical model of two-phase convection in 2D geometry. Our results suggest that water can be generated at the silicate/HP ice interface for small to intermediate values of Rayleigh number (Ra$\sim 10^8$–10^{10}) while no melt is generated for the higher values (Ra$\gtrsim 10^{11}$). If generated, water is transported through the layer by the upwelling plumes and, depending on the vigor of convection, it stays liquid (smaller Ra) or it may freeze (intermediate Ra) before melting again as the plume reaches the temperate layer at the interface with the ocean. The thickness of this layer as well as the amount of melt that is extracted from it is controlled by the HP ice permeability. This process may enable the transfer of volatiles and salts that might have been leached from silicates by the meltwater. Since the HP ice layer is much thinner on Titan than on Ganymede [1], it is probably more permeable for volatiles and salts leached from the silicate core.

1. Introduction

The exploration of ocean worlds is prompted by the question of the emergence of life in places where liquid water has been present. A lot of attention is currently given to Europa and Enceladus where the subsurface ocean is expected to be in a direct contact with the silicate mantle [2,3]. Ganymede and Titan, the largest icy moons in the solar system, are believed to possess larger amounts of H_2O so that a layer of HP ice is predicted in their interior that seems to prevent this direct contact [4]. These two moons are very similar in mass and radius but their radial mass distribution is quite different. Ganymede is likely the more differentiated body with a five layer structure (ice I crust, ocean, HP ice layer, silicate mantle, liquid iron rich core [5]) while Titan is probably less differentiated with a rocky core made of hydrated silicates [6].

While the bulk of the deep HP ice layer prevents a direct contact between the ocean and the silicates, the heat and material exchange between these two layers might still be possible. Recent 3D numerical simulations of thermal convection in the HP ice mantles of large moons [7] indicate the occurence of melting for a broad range of model parameters. However, melt transport is not included in these models and instantaneous melt extraction is hypothesized. Here, we study the dynamics of the HP ice layers of Ganymede and Titan using 2D numerical simulations of two-phase convection that allow us to address the meltwater generation and its transport neglected in the previous study.

2. Numerical model

We treat the layer material as a mixture of two components - solid ice matrix and liquid water which allows us to consistently address melting of ice and the subsequent meltwater transport. Dynamics of such a mixture is described by the equations derived in [8]. Depending on the connectivity of the interstitial water veins system, meltwater can either percolate through the convecting matrix (if the pores are connected) or be locked within the deforming ice and advected by it. The governing equations combine the compressible Stokes system with the advection of temperature and transport of water content by convection and porous percolation. The numerical code is implemented in the open source FEM software FEniCS [9].

3. Results and summary

We computed the reference solution with the layer thickness H=200 km, reference viscosity μ_0=10^{15} Pa s, bottom heat flux q_{s}=20 mW m^{-2}, and percolation threshold ϕ_{c}=1% - our results are depicted in the middle row of Figure 1. The left panel shows the temperature profiles (red - maximum, black - horizontal average) while the right panel shows porosity (volume fraction of water in the mixture). The layer can be divided into three regions: (i) interface with silicates (T_{av}=T_{m}, thin layer with $\phi_{\mathrm{av}}\lesssim$1% present);

(ii) convective interior ($T_{\rm av}<T_{\rm m}$, a small amount of melt present in the upwelling plumes); and (iii) top temperate layer and interface with ocean ($T_{\rm av}=T_{\rm m}$, $\phi_{\rm av}\sim1\%$). Let us note that even though melt is present at the bottom boundary and that water is extracted to the ocean, there is no direct fluid path through the whole layer.

Changing the HP ice layer thickness H changes the convection pattern. While for H=100 km (Figure 1, top), we observe a two-cell convection with two upwellings stable in time that transport water through the layer, for H=300 km (Figure 1, bottom), no water is present at the bottom boundary or within the upwellings. This effect of the layer thickness H is similar to that of the reference viscosity μ_0 in a sense that it significantly changes the Rayleigh number. On the other hand, the heat flux from silicates has a second order effect. The thickness of the top temperate layer as well as amount of extracted melt is controlled by the HP ice permeability.

We can distinguish 3 melt patterns: (i) **Direct connection** between the silicates and the ocean, characteristic for a small value of Rayleigh number (small layer thickness, large reference viscosity) - in this case, the melt produced in the contact with silicates is advected through the convecting layer by the upwelling plumes that are stable in time and space and more melt might be produced before its majority is extracted into the ocean; (ii) **Indirect connection** between the silicates and the ocean (reference case) - melt generated at the bottom boundary freezes and melts again during its ascent before being extracted into the ocean; (iii) **No melt** is produced at the silicate/HP ice interface for large values of Rayleigh number (large layer thickness, small reference viscosity) - the heat transfer by solid state thermal convection is so efficient that the temperature at the interface with silicates is below the melting point.

Overall, we show that water can be generated at the silicate/HP ice interface for small to intermediate values of Rayleigh number. Once generated, the water is transported through the layer by the upwelling plumes. Depending on the vigor of convection, it stays liquid or it may freeze before melting again as the plume reaches the temperate layer at the boundary with the ocean. The thickness of this layer as well as the amount of melt that is extracted from it is controlled by the HP ice permeability. This process constitutes a means of transporting non-ice material that might have dissolved into the melt present at the silicate/HP ice interface. As the moons cool down, their HP ice layers

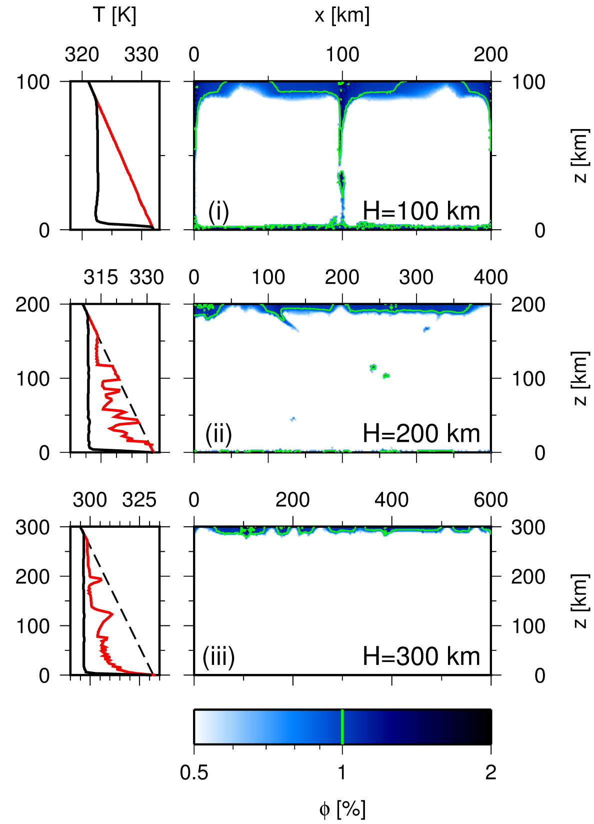

Figure 1: Results for different HP ice layer thicknesses H: 100, 200, and 300 km (top to bottom). *Left*: Temperature profiles - maximum (red) and horizontal average (black). The dashed lines mark pressure-dependent melting temperature ($T_{\rm m}$). *Right*: Porosity. Numbers in the bottom left corners indicate the melting pattern (cf. text).

become less permeable because they thicken. Also, since a thinner HP ice layer is expected on Titan than on Ganymede, our results indicate that the transport of volatiles from the silicate interior to the deep liquid water ocean may have played a more important role in the evolution of Titan.

Acknowledgements

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Test particle simulation of Ganymede's plasma environment

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So far, Ganymede's nearby plasma environment has been in part characterized only during a few flybys of the moon by the Galileo spacecraft at the end of the 1990s and through a few remote observations of auroral emissions by the Hubble Space Telescope. Our knowledge of the plasma composition, density and dynamics in Ganymede's magnetosphere remains therefore limited. The JUICE spacecraft will characterize in detail the exosphere, ionosphere and particle environment around the moon. Prior to arrival, models have been developed to predict these regions and their interaction with the background Jovian particles and magnetic field.

We have developed the first 3D test particle model of Ganymede's ionosphere. The model is driven by: (1) the number densities of neutral species from the exospheric model of Leblanc et al. (Icarus, 2017), (2) solar extreme ultraviolet radiation (Woods et al. 2005), (3) electron fluxes coming from the Jovian plasma around the moon (Mauk et al., 2004) and (4) the electromagnetic field from the hybrid model of Leclercq et al. (PSS, in revision). In the simulation, the ionospheric ions are produced via photoionization and electron-impact ionization of the neutral exosphere. The test particles move under the influence of the magnetic and electric fields derived from the hybrid model.

We will present the first three-dimensional maps of number densities and bulk speeds of the main ion species produced in Ganymede's ionosphere. We will show and interpret our derived ion-impact 2D maps at the surface for both ionospheric ions and Jovian ions (coming from the Jovian plasma sheet), and provide sputtering rates of neutral molecule production resulting from these impacts. We will also quantify the importance of the charge-exchange process between the ions and exospheric species in terms of production of energetic neutrals, which is relevant for exospheric models. Finally, we will assess the variability of the ionosphere over a revolution of Ganymede around Jupiter, driven by the change in the neutral exosphere (Leblanc et al., 2017) and in the angle Sun-moon direction. We will evaluate its potential implications on the variability of Ganymede's magnetic environment.

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The Cratering Record of Ganymede and the Origin of Potential Impactors: Open Issues

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Abstract

The origin of impactors on the Galilean satellites of Jupiter is an open question. Observations and dynamical modeling of potential impactor families and impact rates suggests a prevalence of bodies from the outer solar system, especially the ecliptic or Jupiter-family comets [1]. However, our previous investigations of crater size distributions on the densely cratered Galilean satellites Ganymede and Callisto in specific localities imply an impactor size distribution of bodies derived from a collisionally evolved family, such as, e.g., Main Belt asteroids [2][3]. For detailed scrutiny of crater size-frequency distributions (henceforth termed CSFDs) on Ganymede, we began a mapping campaign based on reprocessed Voyager and Galileo SSI [4] images and on an updated global geologic map [5] in order to derive a thourough data base of Ganymede's crater distribution. This data base is used to infer the size distribution and most likely origin of potential impactors.

1. Introduction and Motivation

Investigating the crater size-frequency distribution of Jupiters largest satellite Ganymede is hampered by the fact that a global coverage with images at regional spatial resolution (i.e., an average of at least ~1 km/pxl) has not been fully accomplished by Voyager and Galileo and varies between ~700 m/pxl (Voyager-2) and ~ 4 km/pxl (trailing hemisphere, imaged by Galileo SSI). In this study, we use these data and an updated geologic map of Ganymede [5] to derive a crater size-frequency distribution data base of Ganymede.

2. Procedure

Voyager images from the two flybys in 1979 and Galileo SSI images [4], especially those filling the two gaps left by Voyager, are reprocessed in order to preserve their respective highest possible spatial resolution, instead of applying an average (lower) map scale for a global basemap. In a second step, spatial (highpass) filtering is applied to enhance small-scale details. These data are used to obtain a global data set of crater size-frequency measurements in the size range larger than ~4-5 km. Locally, we use higher-resolution Galileo SSI images from selected target areas for detailed studies of crater distributions at smaller diameters. Geologic units based on the global geologic map by [5] are mapped with the software package *ArcGIS* by a crater tool plugin to create a crater statistics set from each crater distribution measurement [6]. The software tool *craterstats* [7] is then used to obtain relative and absolute ages.

3. Results

In *Figs. 1 & 2*, CSFDs measured on two of Ganymede's major geologic units in the subjovian hemisphere are shown in relative crater size-frequency diagrams (R-plot) [8]. One set of CSFDs depicted in *Fig. 1* is from older ***dark cratered material (dc)*** [5] in Nicholson and Barnard Regio, measured in Voyager-1 data (spatial resolution: 2 km/pxl; red symbols) and two Galileo SSI target areas (28GSNICHOL01, 127 m/pxl, blue; 28GSNICHOL01, 27 m/pxl, green). *Fig. 2* shows a set of CSFDs from younger ***light smooth material (ls)*** [5] in Harpagia Sulcus, measured in Voyager-1 data (2 km/pxl; violet symbols), and two Galileo SSI target areas (28GSMOOTH02, 120 m/pxl, blue; and 28GSSMOOTH01, 16 m/pxl, dark yellow). The horizontal line represents an equilibrium distribution for small lunar craters [9] (labeled as EF in *Figs. 1 & 2*). The curve shown in *Fig. 1* (red) and *2* (blue) is an 11th-degree polynomial derived from the lunar production function [9] which has been transferred to Ganymede's impact conditions based on crater scaling [10] (labeled as PF in *Figs. 1 & 2*).

Despite the high degree of scattering apparent in the R-plot, both crater data sets broadly render a “dip-and-hill” shape which is highlighted by the curve fitted to the data. The best approximation to the measured CSFDs is achieved by assuming preferentially rocky bodies impacting at comparably low velocities (order of ~5 km/pxl [11]) from planetocentric orbits for the crater scaling law. The shapes of the CSFDs which represent production functions shown by the fitted curve are strongly indicative of impactors from a collisionally evolved projectile family, such as, e.g., Main Belt asteroids, or possibly bodies from a now extinct mixed asteroid-comet family of impacting objects. The size distribution of, e.g., Jupiter-family comets (ecliptic comets) which preferentially impact the Jovian satellites at present time [1] is not rendered in the measured CSFDs, however. The deviation of the CSFDs from the curve at smaller crater sizes (i.e., shallower slope than the curve) may be either caused by (1) geologic processes, such as erosion of small craters, or (2) by saturation equilibrium of small craters. Future imaging data by the Janus camera aboard ESA’s JUICE mission [12] will help to extend the still insufficient data base at small crater sizes towards craters < ~100 m in specific localities.

4. Summary and Outlook

Our results from crater counts in the densely and moderately cratered units on Ganymede (dark and light materials) favor impactors from a collisionally evolved projectile family which (1) could originate from Main Belt asteroids or (2) from an extinct family of impactors. Applying the chronology model by [2] (labeled as CF, *Figs. 1 & 2*), light and dark materials are order of ~3.8 Ga and ~4.1 Ga old, respectively. Our ongoing studies incorporate global crater counts on reprocessed Voyager and Galileo SSI data, studies of selected Galileo SSI target areas at higher resolution, and a comparison with CSFDs from Ganymede’s neighbour Callisto.

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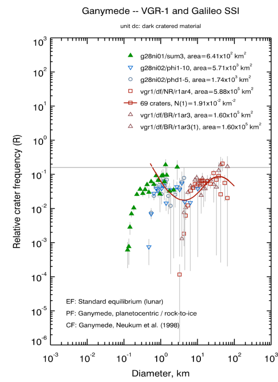

Figure 1: Example of a relative crater-size frequency diagram of measurements from dark cratered materials [5] in Nicholson Regio. Combined measurements from Voyager-1 (red) and Galileo SSI (blue, green) images. Explanation given in text.

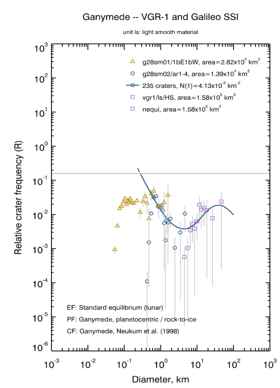

Figure 2: Example of a relative crater-size frequency diagram of measurements from light smooth materials [5] in Harpagia Sulcus. Combined measurements in Voyager-1 (violet) and Galileo SSI (blue, dark yellow) data. Explanation given in text.

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The Ganymede Laser Altimeter (GALA)

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Abstract

The Ganymede Laser Altimeter (GALA) is one of the instruments selected for the first ESA large class mission JUICE. The scientific goals of the GALA instrument cover a wide range of questions of geology, geophysics and geodesy. Here we will present an overview on the scientific goals as well as on the instrument baseline design concept and the current performance analysis.

1. Introduction

The Ganymede Laser Altimeter (GALA) as part of the JUICE payload is one of the instruments focusing on aspects related to the presence and characterizations of subsurface water oceans. For the first time the time-variability of the global figure of a moon due to tides exerted by Jupiter will be detected by altimetry measurements.

By characterizing in detail Jupiter's moon Ganymede the JUICE spacecraft will be the first mission to orbit a satellite of the Solar System other than the Earth's Moon. In addition, flybys at Europa and Callisto will deepen our understanding of the current state and evolution of the Jovian satellite system. GALA will provide fundamental knowledge about Ganymede, Europa and Callisto and will, in combination with other instruments, lay the ground for further exploration of the Galilean satellites by future in-situ missions (e.g., landers or penetrators).

2. Scientific goals

A fundamental goal of any exploratory space mission is to characterize and measure the shape, topography, and rotation of the target bodies. This is essential for understanding the interior state and global aspects of satellite evolution as well as regional and local processes that have shaped the body's surface. A state of the art tool for this task is a laser altimeter because it can provide absolute topographic height and position with respect to a Ganymede (or Europa/Callisto) centered reference system.

With respect to evolution of the Galilean moons, the GALA instrument aims at

• the prove of existence of a global subsurface ocean and further characterization of the water-ice/liquid shell by monitoring the dynamic response of the ice shell to tidal forces.
• measurements of forced physical libration and spin-axis obliquity that would provide additional information on the existence and extent of a subsurface ocean
• provide accurate data for determining Ganymede's shape (A, B and C-axis), local- and global topographic measurements
• detailed topographic profiles crossing the linear features of grooved terrains.
• as well as at information about slope, roughness and albedo (at 1064nm) data from Ganymede's surface

Further GALA will form an integral part of a larger geodesy and geophysics package, incorporating radio science, stereo imaging and sub-surface radar. The synergy will tackle the problems of planetary shape, rotation, gravity field determination, interior structure, surface morphology and geology, and tidal deformations. The latter is crucial for the detection of subsurface oceans on Ganymede (and on Europa and Callisto).

3. The Instrument

The principle of laser altimetry is straightforward. In a laser altimeter, a laser emits a short laser pulse, which is reflected from the surface of the body, received by a telescope and then analyzed by an electronic unit. The time of flight between the emission of a pulse and the receipt of the reflected pulse is measured. This time of flight is converted to a distance using the speed of light.

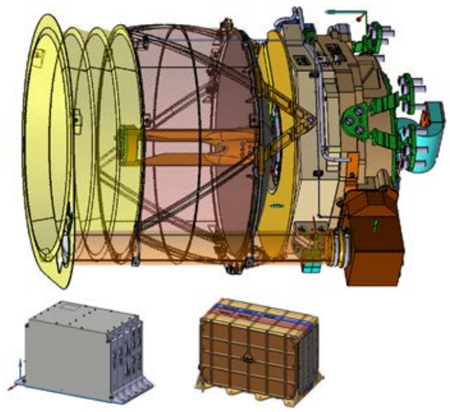

Figure 1: The GALA instrument

As pumping scheme, side-pumping is proposed here due to reduced technical complexity and heritage from the BELA (BepiColombo Laser Altimeter) transmitter laser. Redundancy can be realized easily with this scheme on diode stack level. Table 1 gives an overview on the sub-system parameters. Performance analyses show that the GALA instrument will be able to operate to an altitude of 1300 km and has good signal to noise ratios even when operating in Ganymede's orbit on high sloped terrain or terrain with low albedo.

Table 1: Transmitter sub-system parameters

Parameter	Value/description	Unit
Laser rod crystal	Nd:YAG	N/A
Wavelength	1064	nm
Pulse energy	17	mJ
Pulse repetition rate	30	Hz
Telescope radius	13	cm
Field of view	580	µrad
Optical efficiency	0.85	N/A

5. Summary and Conclusions

The diversity of targets and the different phases of the trajectory including flybys and orbital phases during the course of the JUICE mission require flexibility of the instrument to achieve the various scientific objectives. Therefore GALA is built up on a two resonator design in order to fulfill the scientific requirements. During the mission a wide range of questions related to geology, geophysics and geodesy will be covered.

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Imaging of energetic neutral atoms with the Jovian Neutral Atoms Analyser onboard JUICE: Charge exchange ENAs near Ganymede

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Abstract

The Jovian Neutral Atoms Analyser (JNA) is one of the sensors of the Particle Environment Package (PEP), which is one instrument suite of the JUICE scientific payload. Mapping of the energetic neutral atoms (ENAs) in the Ganymede magnetosphere, will offer valuable clues about the interaction of the Jovian plasma with the icy moon's surface and the magnetospheric plasma processes. We will present expectations of neutral fluxes, particularly neutrals produced via charge exchange, in the vicinity of Ganymede. From these expectations from our model we infer the expectations for JNA measurements.

1. Introduction

The Jovian system is subject to complex plasma physics processes and can therefore be considered as a giant particle accelerator. Due to the plasma interactions, the Jovian moons are affected by diverse processes that lead to a vast range of space weathering effects and to a constant mass input to the environment of the moons.
Ganymede possesses a strong intrinsic magnetic field that imposes restrictions on the possible trajectories of plasma ions in the Ganymede magnetosphere [1]. As a result, certain terrains on the surface of the Jovian moon are protected against space weathering processes while others are not.

The JNA onboard the JUICE spacecraft will measure energetic neutral light and heavy atoms in an energy range from 10eV to 3keV [2], which covers the energy range of ENAs emanating from various different ENA production mechanisms. Low energy ENAs produced via sputtering and backscattering will be used to image the precipitation regions and, in particular, a boundary of open and closed field lines. In addition, ENAs are expected to be produced by the charge – exchange mechanism in the vicinity of Ganymede. From the measurement of these ENAs, we can infer the global plasma distribution in the Ganymede magnetosphere.
In this study we investigate the interaction between the Jovian plasma and the Ganymede magnetosphere and exosphere. In the Jovian system these interactions of the co-rotating magnetospheric plasma with the icy moons give rise to several observative effects, like for example the UV-aurorae observed on Ganymede [6].
The energy balance in terms of mass and radiation balance is one key scientific question of the mission as well as the surface and exosphere composition of the Jovian moons [4]. The direct measurements of mass flux by the JNA will undoubtedly contribute to answer these questions.

2. Model

To calculate the expected fluxes of ENAs as well as the number of ENAs from the charge exchange processes, we combined the plasma spatial distribution modelled by hybrid simulation [5], the exospheric density model for Ganymede [8], and the charge exchange cross sections [7]. Using a hybrid model, we derived the fraction of ENAs from charge exchange processes and the expected neutral fluxes in the JNA instrument.

Fig. 1 shows the plasma ion locations from [5] in the GPhiO system as a snapshot in time. In the graph, ions are shown in white colour, thus bright regions designate higher plasma density. The co-rotating Jovian plasma precipitates on the Ganymede magnetosphere from the rear, causing a void in front of the moon, appearing in black in Fig.1, seen in direction of its trajectory along the orbit.

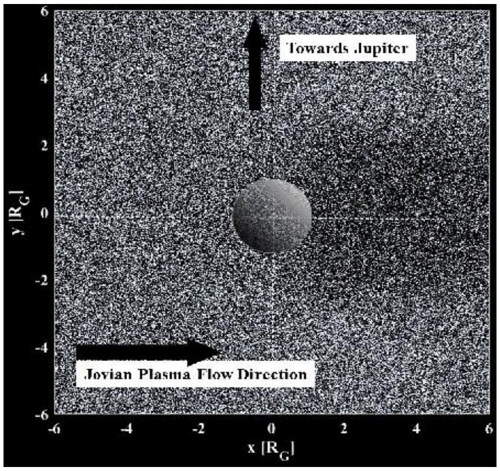

Figure 1: Plasma spatial distribution in the vicinity of Ganymede, reproduced from [5].

3. Summary

The JNA instrument, one of the sensors of the PEP scientific payload on the JUICE mission, will measure ENAs in the Ganymede magnetosphere and exosphere. These measurements will greatly contribute to our understanding of the interaction of the Jovian plasma with Ganymede, its icy surface and its intrinsic magnetic field. Based on a hybrid model we derived the neutral fluxes produced by charge exchange processes of high energetic plasma particles and neutral atoms in the Ganymede exosphere and the resulting fluxes expected to be measured by the JNA. We present our model, the resulting observations for species heavier than N and the ENA fluxes along the JUICE Ganymede orbit expected to be measured by the JNA instrument.

Acknowledgements

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Europa and Ganymede's Water-Product Exospheres.

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Abstract

Europa and Ganymede are thought to possess globally similar exospheres, in spite of the possibility that Europa is currently cryovolcanically active, and Ganymede's intrinsic magnetic field. Ions in Jupiter's magnetosphere bombard the icy surfaces, and produce predominantly O2, with slightly less H_2O and H_2 due to freezing and escape respectively. We investigate and compare the water-product exospheres of the two satellites under rotation, using our 3-D Exosphere Global Model (EGM). In previous works ([1], [2]), we focused on the *near-surface* $z < 1.25r_s$, oxidized component of the exosphere, dominated by thermalized O_2, which undergoes a dusk-over-dawn asymmetry due to diurnal solar insolation of the surface over the satellite's orbit. This was observed by asymmetries in oxygen aurorae. Here, we focus on characterizing the hydrogen-species: H, H_2, and H_2O which have been far more elusive as lyman-α auroral emission has multiple production pathways, even in the absence of endogenic sources.

1. Introduction

Water is produced exogenically on Europa and Ganymede by two mechanisms: sublimation and magnetospheric ion sputtering. The former yields a thermal profile of water vapor which is quite similar to molecular oxygen. The latter is energetic as the water molecules are thought to leave the amorphous (Europa trailing) or crystalline (Ganymede) water ice lattice at high velocities. A portion of these water molecules undergo radiolysis in the regolith, and eject large quantities of molecular hydrogen and oxygen, in a 2:1 ratio. Smaller quantities of atomic hydrogen along with other trace species are also thought to be ejected into the exosphere. The sputtering production rates are difficult to constrain in the laboratory, due to uncertainties in surface ice concentration, grain sizes, and porosities. At Europa, we have employed the globally-averaged sputtering rates by [3] and find that these rates are able to reproduce the behavior and magnitude of the near-surface O2 component reasonably well [1]. However,auroral profiles by the HST seem to suggest the corona $z \gtrsim 1.25r_s$, is in an energetic state of expansion. One mechanism could be O2 collisions with the background H_2O and H_2 atmosphere mentioned above. Additionally, the interaction with the Io-plasma torus could result in ion-neutral scattering of the near-surface component, enhancing escape rates, which are uncertain at the present. At Ganymede, [2] showed that uncertainties in water vapor sublimation fluxes can produce vastly different behavior of the H_2O column density over the orbit.

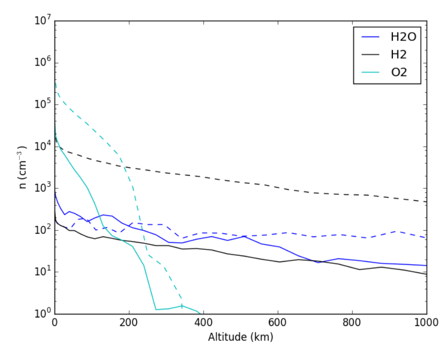

Figure 1: Surface densities for the dominant species in Europa (solid) and Ganymede's (dashed) exospheres at the sunlit trailing hemisphere.The H_2O case represents a low-sublimation case[2].

1.1. Observations

Recently, [4] has helped constrain the atomic hydrogen column density at Europa, via HST transit observations. The Ly-α absorption at 1216 Å appears to indicate a column of $N \sim 10^{12}$ H cm^{-2} corresponding to ~ 80 Rayleighs of hydrogen auroral emission. The derived number densities range from $n_E \sim 1.5 - 2.2$ H cm^{-3}. Comparing to Galileo observations of Ganymede by [5], the derived atomic hydrogen surface densities at Ganymede are larger by a factor of ten, with an emission of ~ 560 Rayleighs.

2. Exosphere Modeling

We simulate the icy satellite exospheres by employing a parallelized Monte Carlo routine we refer to as an Exosphere Global Model (EGM). We track particles in a rotating, non-inertial reference frame, in spherical coordinates (r, θ, ϕ), extending up to $\sim 15r_s$. Ejected test particles are on ballistic (collisionless) trajectories, and can escape, stick, and be re-emitted from the surface depending on their surface interactions. At Ganymede, the magnetic field impedes low latitude sputtering, particularly on the ram facing hemisphere. In this way, most exospheric production in the low sublimation case, occurs at the poles. Most relevant for this work are the numerous electron impact and photodissociation reactions of H_2O and H_2, tabulated in [2]. These reactions are critical to the production of atomic hydrogen and the resultant Ly-α emission as H sputtering is thought to be $\sim 1\%$of H_2O. Figure 1 presents our simulated atmospheric density profiles of Europa and Ganymede for water, molecular hydrogen, and molecular oxygen, the dominant 'background' atmosphere for the trace atomic hydrogen.

3. Results and Discussion

We simulate the orbital evolution of the dominant hydrogen species to gain an understanding of the range of column densities Europa and Ganymede experience throughout their orbit (Figure 2), some of which will be observed as Ly-α emission. These simulations represent modest cases, where there are no enhancements due to ion interactions, nor are there endogenic water plumes contributing to the exospheres. This permits one to first assess the steady-state component of the exosphere, and its orbital variations. From sunlit trailing to leading, we calculate Europa's exosphere to decrease by $\sim 36\%$ in atomic hydrogen, 60% in H_2, and 43% in H_2O. The atomic hydrogen column is $\sim 10^{10} Hcm^{-2}$, whereas H_2 and H_2O are $\sim 10^{13} cm^{-2}$. Ganymede's atomic H ($N_H \sim 10^{11} cm^{-2}$) peaks at the poles and also decreases by $\sim 50\%$, whereas H_2 ($N_{H2} \sim 10^{15} cm^{-2}$) and H_2O ($N_{H2O} \sim 10^{14} cm^{-2}$) fall by an order of magnitude at sunlit leading.

The observed hydrogen column densities appear to be 1-2 orders of magnitude higher than our atomic H simulations, possibly suggesting more efficient atomic H sputtering rates, or more efficient exospheric H production via H_2 and H_2O. A similar conclusion was reached in the case of Ganymede with respect to Galileo observations [2], where it was suggested that e^- impact of H_2O may be a source of Ly-α emission.

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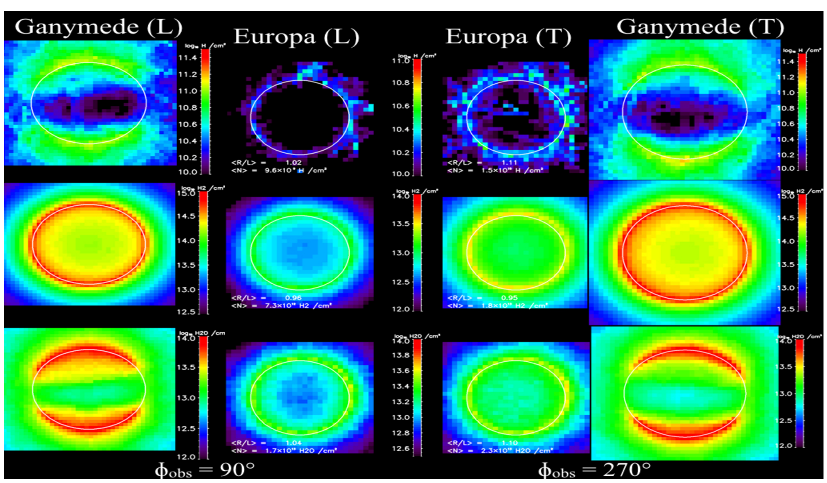

Figure 2: Line-of-sight column density maps for the dominant hydrogen species on Europa and Ganymede. The right hand side is the sunlit trailing hemisphere, and the left hand side is the sunlit leading hemisphere.

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Transpressional tectonics on Uruk Sulcus, Ganymede

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Abstract

Ganymede shows an icy crust strongly shaped by past and possibly still active tectonics. Kilometric morphotectonic features, grooves and furrows, develop within the light terrain and the dark terrain, respectively. Open debate exist on the geodynamic processes responsible for these features. In this contribution we explore the tectonic setting of the light terrain region of Uruk Sulcus. We classify three groove systems and one furrow system within the sulcus using methodologies of structural geology. An automatic lineament domain analysis was progressed and results were compared with the recognized groove/furrow systems giving insight on the stress field in the study area. Obtained results concern the relative deformation intensity and the rheology within the crust of the studied region. We found that Uruk Sulcus is a corridor characterized by a dextral transpression, approximately N-S oriented, that in turn is responsible for localized transtension among crustal blocks within the shear zone. Being the target area of the radar sounder RIME (Radar for Icy Moon Exploration) for ESA's upcoming JUICE (JUpiter ICy moon Explorer) mission, the present work aims also to contribute to the scientific preparation of this mission.

1. Introduction

The icy surface of Ganymede is globally divided into two terrains, the light terrain and the dark terrain [1], deformed by diffused secondary features including craters and linear structures. The latter correspond to kilometric subparallel, linear and subcircular ridge and trough systems [2] , [3] and are considered evidence of tectonic activity deforming the crust. Furrows are the main tectonic features occurring within the dark terrains, and the light terrains are intensely etched by grooves. Authors [3] proposed extensional tectonic models to explain groove formation. On the other hand, evidence of compression has not been yet recognized, leaving open the research to clarify the tectonic balancing on Ganymede surface. The investigation on the surface deformation is still open and aid to understand the internal processes of this satellite.

2. Methodology and data analysis

2.1 Groove/furrow system detection

Specific processing of Voyager and Galileo images allowed the preparation of a high-resolution mosaic (with maximum resolution up to 50 m/pixel) of the anti-jovian area framing the Uruk Sulcus (Fig. 1). Groove and furrow of Uruk Sulcus region were carefully identified, for a total of 795 elements.

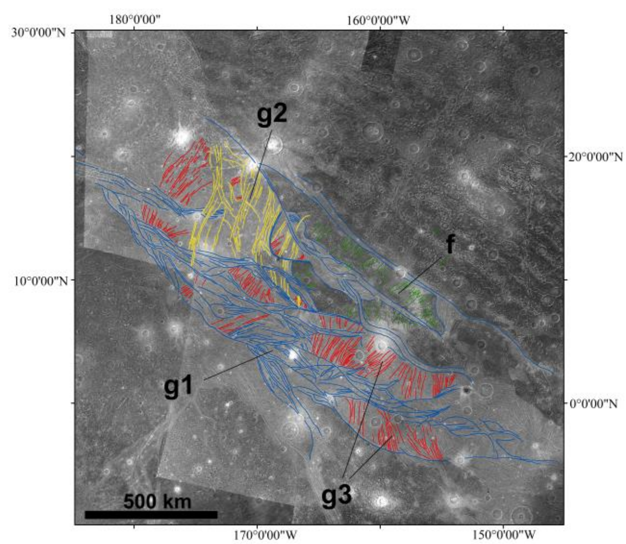

Figure 1: Groove and furrow systems recognized within Uruk Sulcus.

These structures were grouped into systems based on their features together with their spatial and crosscutting relationships and were quantitatively characterized by morphology, sinuosity, location, azimuth, and length. For each system, azimuthal analysis of multiple and single elements by frequency and cumulative length was performed. The azimuthal analysis was performed by a polymodal procedure best fit with a family of Gaussian curves that show the independent azimuthal groups within each system with their statistical parameters [4], [5]. We measured, for each group, the mode/sd ratio that represents the sharpness of the corresponding population. The texture of the spatial distribution of the systems was represented by the ratio L/S where L is the structure length and S is its distance with the closest structure belonging to the same group [6]. These analyses allowed to recognize 3 main groove systems, namely g1, g2, g3, together with a furrow system (f) (Fig. 1).

2.2 Lineament domains detection

Automatic lineament detection was performed to understand the kinematic/dynamic setting of Uruk Sulcus. Lineaments derive either from the geodynamic stresses, the dynamic lineaments, or from movements within shear zones, the kinematic lineaments, as along strike-slip regional faults [7]. Results show the presence of a kinematic related NW-SE lineament domain and a sharp NNE-SSW lineament domain resulting from a surface stress field with maximum horizontal stress (Sh-max) parallel to it (Fig. 2).

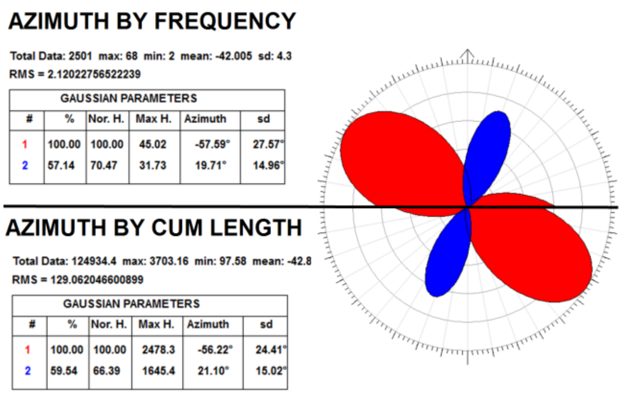

Figure 2: Lineament azimuthal analysis showing two lineament domains.

3. Discussion and conclusions

The comparison of the groove/furrow systems with the lineament domain analysis allows to propose a tectonic model for the investigated area. Uruk Sulcus represents a right-lateral strike-slip corridor with evidence of transpression (up to 70% of compression) responsible for the development of the stress-parallel NNE-SSW lineament domain. The NW-SE g1 groove system relates to the shear along the corridor. The NNE-SSW g2 groove system represents the antithetic structures given by the shear. The NE-SW g3 groove system relates to the internal stress conditions induced by the shear.

Acknowledgements

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Exchange processes in the deep icy layers of Ganymede: numerical and experimental approaches

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Abstract

This research project is aimed at studying the Exchange Processes occuring in the deep icy layers of the giant moons of Jupiter (Ganymede, Callisto), Saturn (Titan). These planetary objects possess deep oceans trapped in between an upper thick icy shell and a lower solid mantle composed of high-pressure polymorphs of water ice. Our goal is to determine the efficiency of heat and chemical transport through the deep icy mantle from the silicates in the core to the liquid water reservoir, a preliminary requirement to assess the habitability of these deep aqueous environments.

1. Scientific goals

To have a better understanding of the putative habitability of a liquid layer trapped within thick icy mantles, a comprehensive description of the internal layers that constitute the hydrosphere is required, both in terms of structure and dynamics. A special focus must be given to the high-pressure icy layer (fig.) through which both energy and material might be exchanged from a silicate core to the liquid reservoir.

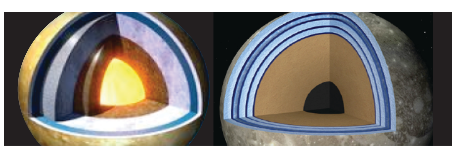

Figure : Two types of structures for large icy moons. Left: "classical" model (Credit: Dominic Fortes ucl.ac.uk) - the liquid layer is trapped in between an upper icy crust and a thick high-pressure icy mantle. Right: Multi-layered structure[1]. Due to the density contrasts between liquid water and solid phases (water ices, hydrates), several liquid layers may be trapped in between icy mantles. By studying the properties of the interfaces at melting temperature, new insights into the characteristics of the deep internal structures might be gained.

Our project is tailored as follows:

- at laboratory scale, a setup is currently designed to determine and to quantify energy and chemical transfers through a convecting layer melted on its upper boundary (section 3).
- Relevance for planetary objects of the physical processes identified in the experiments is not straightforward. A numerical assessment of this property is under study (section 4).
- The scaling laws to be used at planetary scales will be derived from the combination of both experimental and numerical approaches. A thorough analysis of their robustness at all planetary scales is planned.
-

2. From planetary interiors to the laboratory scale

While not directly answering the question of habitability, observations from Galileo and Cassini-Huygens missions hint at a preamble: the presence of the deep icy mantle does not rule out the possibility of chemical exchange between the rock component and the hydrosphere at some point of the moons' history: geophysical models favour internal oceans with a significant concentration in salts (high density for Titan, cf. e.g. [2], conducting for Ganymede [3]). The detection of ^{40}Ar by the Huygens probe [4] even suggests that products of rock/water interactions made their way up to Titan's atmosphere. Whether such exchanges occurred mostly during the early formation/differentiation of these objects or later on is however ambiguous.

Understanding the nature of heat/chemical exchanges through the deep icy layers thus requires an investigation by dedicated experimental and numerical modelling work. A preliminary study depicted an efficient transport of liquid water from the interface with the rock core up to the ocean, through warm/partially molten chimneys in an otherwise globally cool icy matrix [5]. Investigation of a wider range for HP ice viscosity nevertheless modulates this result of efficient melt extraction through heat pipes: lower viscosity values might induce other dynamical regimes (see the presentation by Kalousovà in this meeting) - the most recent history could even involve the cessation of ice melting at the interface with the rock core.

Such models ultimately adopt the simplistic description of a prescribed phase change boundary between the deep ice and the ocean. Recent work on solid-state convection with an evolving melting/freezing front indicates that the development of heat pipes in the ice is indeed a viable mechanism [6]. But again, this relies on strong assumptions on efficient heat redistribution in the liquid layer. The present project precisely aims at an independent laboratory assessment of such hypotheses in the framework of deep interiors of icy planets/moons.

3. A 'down to Earth' approach: similarity and scaling arguments

One important issue with experiments like the one foreseen for this project is to ensure that all physical dimensions are scaled in the same way. Convective processes taking place in the deep icy layers of icy moons are characterized by huge space and time scales (thousands of kilometres and millions of years, respectively). This imposes stringent requirements on the design of the experimental setup, which should be properly scaled down.

As table top experiments are first constrained by finite pressure gradients, an extra pair of thermodynamic conjugated variables needs to be supplied in order to cross the phase change line. One option is to generate a controlled stress field and attempt to shift the phase change line to an experimentally observable point according to a generalized Clapeyron - Clausius correlation. To do so we propose an experimental arrangement consisting of a table-top flow system with precisely controlled moving vertical boundaries. Along the vertical direction, cavity will be heated differentially and the vertical position of the phase-change line will be adjusted by carefully tuning the external stress field. A second point that needs to be addressed is related to the hydrodynamic and thermal similarity with the planetary system. Preliminary scaling arguments indicate that the icy-water system can be replaced at a laboratory scale by paraffin which exhibits a phase transition at around 56^{o}C, behaves as a thermo-rheologically simple fluid above and as a highly viscous solid below.

The main results of this preliminary analysis will be displayed at the meeting.

4. Setup of the numerical approach

Our purpose is to provide a robust numerical model complementary to the experimental approach. The experimental setup induces thermal convection-diffusion in solid paraffin leading to the melting of the material. The key issue is to account for the moving liquid-solid phase boundary. In particular, it is mandatory to depict precisely the interface topology and the thermal and mass exchanges arising.

If one assumes that the phase change is isothermal, then one ends up with a sharp interface model. In that case a Stefan-like problem is considered. We design an Arbitrary-Lagrangian-Eulerian numerical method with random projection to capture the sharp interface. Significant progresses have already been obtained on that complex subject [7]. Conversely when considering a non-isothermal melting, the interface is diffused, thus leading to the appearance of a mushy region. In that case, the model consists in the Navier-Stokes equation coupled with thermal convection-diffusion. The position of the interface is not defined explicitly but is indicated by the liquid fraction in the domain. The numerical approach considered for this model is an enthalpy-porosity method [8].

Preliminary results of both numerical methods compared with test-cases from the literature will be presented. The first objective of part 4 is to apply these numerical models to validate the experimental results of part 3. Second, it will allow setting the scaling laws that shall be used at planetary scales.

Acknowledgements

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Global ice flow on Europa

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Abstract

Europa is one of the most probable places in the solar system to find extra-terrestrial life [1], motivating the study of its deep ($\sim$100 km) ocean [2] and its thick (many kilometers) icy shell [2]. Recently, the Hubble telescope discovered water vapor plumes over Europa's southern pole region [3], strengthening the evidence for an underlying ocean. The observed chaos terrain patterns on Europa's surface [4] were interpreted, among other mechanisms, as a signature of vertical convective motions within the ice [5]. Horizontal gradients of ice thickness [6] are expected due to the large equator-to-pole gradient of surface ice temperature, and can drive a global horizontal ice flow; yet the dynamics of such a flow and its observable implications were not studied.

Here we present the first global ice flow model for Europa, composed of a soft flowing ice under a rigid cold external ice crust, under the influence of tidal heating and coupled to a global underlying ocean. We show that Europa's ice can indeed flow meridionally due to pressure gradients associated with anomalies in the ice thickness of up to a few kms. Observable gradients of ice thickness are reduced both by ice flow and due to ocean heat transport when included. The ice thickness and meridional flow direction depend on whether the ice is convecting or not, and multiple equilibria are found in some parameter regimes.

Future missions to Europa such as the *JUICE* of ESA and *Europa*, *Clipper* of NASA are expected to measure the ice thickness and surface temperature, which can be used together with our global ice model to deduce whether Europa's icy shell is convecting, to estimate the effectiveness of ocean heat transport, and more.

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Cryomagma ascent on Jupiter's moon Europa

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Abstract

Smooth plains and lobate features are identified on Europa's surface, and among other features seem to involve sub-surface liquid water reservoirs at shallow depth. Our study aims at modeling the ascent of liquid water from a freezing chamber to the surface, producing cryovolcanic eruptions. We show that if this kind of liquid flow takes place on Europa, the eruptions happen in a short time scale (tens of seconds to tens of hours), and the cryolavas travel to the surface at high speed (few tens of m/s) as a turbulent flow.

1. Introduction

Data acquired by the Galileo spacecraft between 1995 and 2001 show diverse geological features on Europa [3]. These features associated with a low craters density at the surface demonstrate an internal activity of the moon [5]. In particular, smooth plains cover parts of the surface, and their morphologies and relationship to the surrounding terrains suggest that they result from viscous liquid extrusions [9].

Recent literature involves the presence of liquid reservoirs beneath the surface to explain the emplacement of common features, such as double ridges [2], lenticulae [6] and chaos [10].

The aim of this study is to define the conditions and timing of ascent of liquid water, and whether or not liquid water extrusion from sub-surface reservoirs can produce the smooth plains and lobate features. In order to do this, we first model the ascent of water through a dike or a pipe-like conduit for Europa's surface conditions and different chamber depths and volumes.

2. Model

We first test one of the trigger mechanism proposed by Fagents [3]: at the first stage, a liquid water pocket is present in the subsurface. For instance, this pocket may either come from the global ocean underneath, captured by the convective movements within the ice shell [8], or may be due to local enhanced heat flux [4]. Second, the cryomagma contained in the chamber freezes and pressurizes over time. When the stress applied on the chamber's walls reaches a threshold, the walls break and the fracture may propagate to the surface. Third, the remining fluid (that did not crystallize) flows out at the surface through a dike or a pipe-like conduit.

We model the flow driven by the pressure difference between the cryomagma reservoir and the surface. After eruption initiation, the pressure in the chamber decreases with time and the eruption stops once the pressure in the chamber is equal to the hydrostatic pressure.

The overpressure required to fracture the chamber depends on the chamber depth H, the ice shell density ρ_i and the ice tensile strength σ_c [7]:

$$\Delta P_{max} = 2(\sigma_c + \rho_i g H) \quad (1)$$

The pressure increase generated by the cryomagma freezing is related to the liquid volume decrease through the water compressibility χ:

$$\chi = -\frac{1}{V}\frac{\partial V}{\partial P} \quad (3)$$

An estimation of the Reynolds number for such flow leads to a typical value of $Re = 10^7$. Assuming a turbulent velocity [1]:

$$U = \sqrt{\frac{D_h(P_c - \rho_w g H)}{2 f \rho H}} \quad (3)$$

with H the chamber depth, P_c the overpressure inside the chamber, D_h the dike or pipe-like conduit hydraulic diameter, ρ_w the water density and f the friction factor inside the conduit. We calculate the evolution of flow velocity and chamber pressure with time. The simulation also returns the total volume of water extruded at the end of the eruption.

3. Results and conclusions

We investigate the influence of the dike/conduit geometry and the chamber depth and volume on eruption duration and emitted volume. We find that the results obtained depend mostly on the two last parameters.

As an example, Fig. 1 and 2 show respectively the evolution of the pressure in the chamber and the evolution of the mean velocity of the flow for a 2 km depth chamber, which has a total volume of 1km³. We assume a dike of 100 m² cross-section through which the liquid water ascends to the surface.

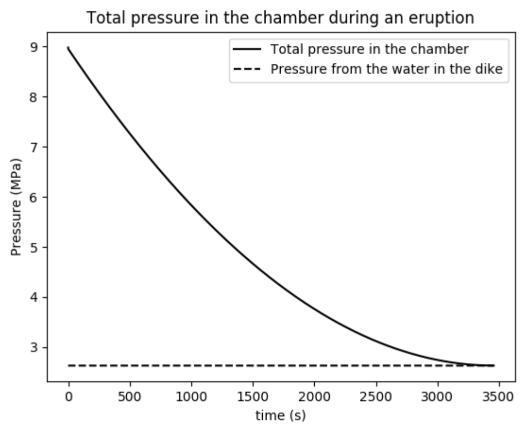

Figure 1: Evolution of the pressure inside a chamber of 1km³, 2km depth, during a cryovolcanic eruption. The eruption stops when the pressure in the chamber equals the pressure of the water column into the dike.

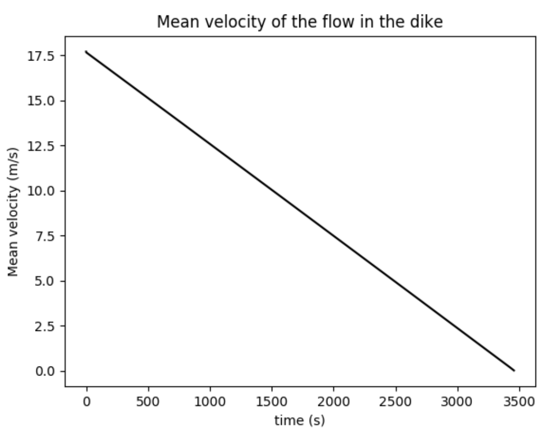

Figure 2: Evolution of the mean flow velocity from a chamber of 1km³, 2km depth, during a cryovolcanic eruption. The eruption stops when the pressure in the chamber equals the pressure of the water column into the dike.

The eruption time-scale and total volume extruded at the end of the eruption depend on the chamber volume and depth. For plausible volumes and depths varying between $0.1\,km^3 < V < 10\,km^3$ and $100\,m < H < 10\,km$, the total extruded cryolava volume ranges from 10^5 to 10^8 m³, and the time scale of the eruptions varies from few minutes to few tens of hours.

We plan to investigate the liquid water stability and thermal transfer when the cryomagma approaches the surface. Indeed, the zero pressure and 100 K at Europa's surface may affect the rheology of the flow and the eruptive style. In the future, it would allow us to compare our results with Galileo high resolution images.

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Reconstruction of Callisto's Valhalla basin using n-body and SPH simulations

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Abstract

We present results of n-body and smooth particle hydrodynamics (SPH) simulations, exploring the crater formation process of the Valhalla crater located on the Jovian Moon Callisto. We compute typical impact velocities and impact angles which we then use as input for the SPH simulations to reconstruct the actual crater formation. Using a three-layered Callisto model with a subsurface ocean, we find significant connections between the crater formation process and the interaction with the subsurface ocean. We also investigate the properties of the projectile and numerical effects of low-resolution projectiles in the context of SPH.

1. Introduction

Recently, subsurface oceans have moved into the focus of interest, especially when it comes to possible habitable regions in our Solar System. Jupiter offers icy moons which possibly have such oceans underneath their icy crust. We investigate a possible subsurface ocean of Callisto, Jupiters outermost big moon ([11],[12]).
Typically, subsurface oceans are found by satellite missions and advanced observation techniques ([5],[7]). We show our method to reconstruct the interior of Callisto. We reconstruct its biggest crater the Valhalla crater with some hundreds of kilometers in diameter and we reveal information about deeper layers.
Valhalla as well as other big impact basins were first found by the Voyager probes and analyzed in more detail later during the Galileo mission. The Valhalla crater system measures approx. 3000 km in diameter, containing a bright central area of about 700 km, a ridge system as well as a ring system in the outskirts of the crater. The crater formation process itself is very complex and many details are still poorly understood. We study the origin and the properties of the projectile, as well as the Valhalla crater formation process, and the inner structure of Callisto.

2. Methods

For the n-body simulations we use the Sun, Jupiter, Ganymede and Callisto as massive bodies and measure the moons collisions with a randomized set of initial particles. We determine impact velocities, impact angles, as well as other relevant information for further statistical analysis. We found typical, maximum, relative velocities to Jupiter to be $v_{\mathrm{rel,orbital}} = 670\,\mathrm{m/s}$, $v_{\mathrm{rel,radial}} = 65\,\mathrm{m/s}$ and $v_{\mathrm{rel,vertical}} = 4534\,\mathrm{m/s}$.
We perform the SPH simulations ([9],[14],[16],[17]) with the miluphCUDA code ([19]), designed to accurately model collision events of solid bodies including self-gravity and using the CUDA GPU-computing interface of Nvidia.
The three-layered inner structure we use for Callisto comprises a liquid water mantle of 100 km and an icy crust of 150 km in thickness on top of the core ([1],[2],[3],[6],[10],[13],[18],[20],[21]).

3. Results and conclusion

The collision analysis for the moons significantly favours retrograde impacts and particles which already had their closest approach to Jupiter. The high number of impacts in our simulation results in plausible impact velocities between 9 km/s up to 20 km/s. Apparently, there is a correlation between the impact angle and the latitude of the crater, favouring slightly steeper impact angles of about 40° (with 90° being a grazing impact) ([8]).
We use the newly attained knowledge of typical impact velocities and impact angles to perform SPH simulations of the impact itself. Knowing the velocities and angles, we constrain the mass limits for the projectile for different crater sizes.
Figure 1 shows the fully developed, temporary, transient crater with a diameter of about 350 km ([15]). During the following modification phase, the crater

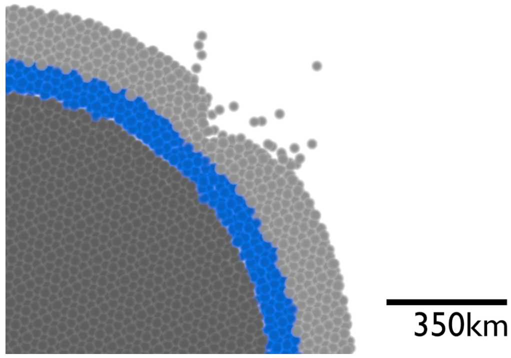

Figure 1: The transient crater disappears again during the following modification phase.

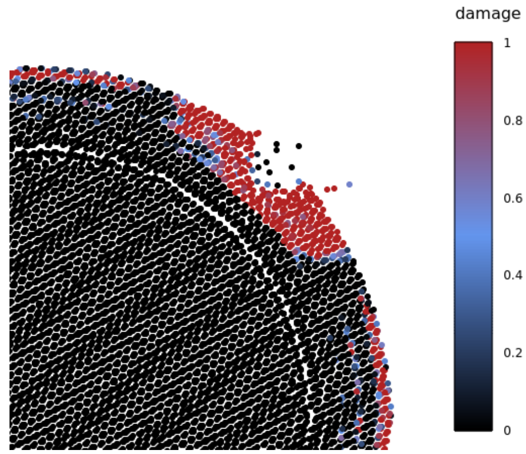

Figure 2: The damaging of the ice shell is caused by the impact event. Note the ring structure as indicated by the undamaged area around the crater.

completely disappears and leaves a distorted surface, resembling observation data ([4]). Figure 2 shows the pattern of damaged material shortly after the impact. The results suggest that a non-damaged ring surrounds the crater, whereas the icy shell may break up due to large pressures from below.

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A stellar occultation by Ganymede

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Abstract

A detection of Ganymede's exosphere was attempted by taking advantage of a favorable stellar occultation event happened on 2016. Observations were conducted from NASA IRTF at Hawaii and from Sobaeksan Optical Astronomy Observatory in South Korea. The event was disturbed by unfavorable weather conditions, mainly at the Hawaii site. The results of light curves analysis will be discussed, as well as the next observing opportunities before the expected JUICE mission arrival in the Jovian system.

1. Introduction

The first clear evidence of an exosphere at Ganymede was found by Galileo-UVS through H Lyman-α emission [1], followed by the detection of far-UV atomic O airglow emissions by HST-GHRS [2] and further evidence for neutral H by HST-STIS [3]. These detections, together with their spatial distribution and to the detection of an intrinsic magnetic field of the satellite [4], reconnecting with the Jovian magnetic field and partially shielding the surface equatorial latitudes from the electrons impact, brought to ascribe the UV observations to auroral processes, signatures of dissociated molecular oxygen in an exosphere [5],[6]. Nevertheless, the physical mechanisms governing these processes are not known with certainty, e.g. whether the emissions morphology is determined by the spatial distribution of magnetospheric electrons or by an uneven O_2 exosphere or both [7]. Furthermore, an extended dust environment has been detected by in situ instruments on board Galileo spacecraft..

2. The 2016 stellar occultation

On 2016 April,13th the Jovian satellite Ganymede occulted a 7th magnitude star. The predicted occultation track crossed the Northern Pacific Ocean, Japan, and South Korea. Hence, it was a very favorable event due to the star brightness and to the visibility from the large aperture telescopes at Hawaii. While no other similar event is expected for the next 10 years, only two occultation events are reported in literature in the past, from Earth in 1972 [8] and from Voyager [9] and their results were in large disagreement in respect to the atmosphere detection.

3. The observations

Two main telescopic observations have been set up to look for exospheric signatures in the occultation light curves. At Mauna Kea (Hawaii) the NASA-IRTF telescope was used covering visible and near-infrared spectral ranges with two instruments simultaneously (MORIS [10] and SpeX [11]), while Sobaeksan Optical Astronomy Observatory (SOAO) acquired visible-range images from South Korea. IRTF instruments were fed by the same optical entrance through a dichroic beam splitter at 0.95μm. Given the short time of exospheric region crossing, all instruments were used with an acquisition frame rate as high as possible, which resulted in about 4 Hz for MORIS, 0.35 Hz for SpeX and 0.2 Hz for SOAO.

The occultation tracks were slightly different from the two observing sites, as shown in figure 1. Despite it was a very favorable event due to the star brightness and to the visibility from the large aperture telescopes at Hawaii, the event has been spoiled by unfavorable weather conditions, that severely reduced photometric accuracy at least at Hawaii. Observations, results, and future similar opportunities before the arrival of the JUICE mission in the Jovian system will be illustrated and discussed.

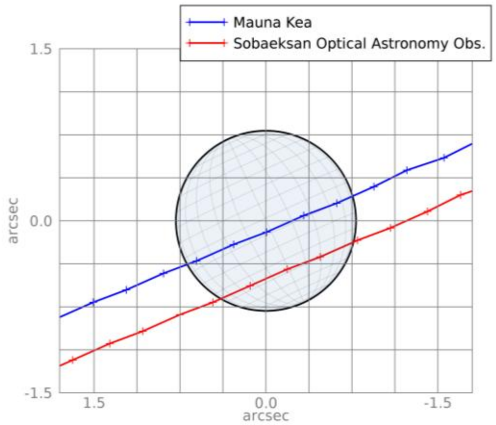

Figure 1: star tracks in respect to Ganymede from the two observing sites during the 2016,April occultation.

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The MAJIS visible/NIR imaging spectrometer on board the ESA JUICE mission : updated design, implications for performances and science goals

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Abstract

MAJIS is the Visible/Near IR imaging spectrometer of the JUICE mission, the first « large » mission of the « cosmic vision » program of ESA, which will study the system of Jupiter with a specific interest for Ganymede during an orbital phase of at least 150 days. The MAJIS consortium involves laboratories and industrial partners from France, with CNES as the lead funding agency, Italy, with support from ASI, and Belgium, with support from BELSPO. The design of the instrument has been consolidated in preparation to the PDR. The operating wavelength ranges of the two channels, initially 0.4 – 1.9 µm for the VIS-NIR channel and 1.5 – 5.7 µm for the IR channel, are now 0.5 – 2.35 µm for the VIS-NIR channel and 2.25 – 5.54 µm for the IR channel. This shift of the crossover to a longer wavelength has made it possible to simplify the optical design while maintaining or improving the science performances. The passive cooling scheme has been confirmed, with an extension of the surface of the radiators so as to provide adequate margins for the required operating temperatures (≤ 140 K for the VIS-NIR detector, ≤ 90 K for the IR detector). H1RG detectors from Teledyne have been selected. These detectors are 1024 x 1024 pixels in size with a pitch of 18 µm. The effective area for photon collection will be constituted by 800 lines of 1016 pixels. Binning by 2 in the spatial direction will be implemented, with an IFOV of 150 µrad and a FOV of 0.06 rad. The nominal operating mode will implement binning by 2 in the spectral direction (508 spectral samples), providing a spectral sampling of 3.65 nm for VIS-NIR channel and 6.49 nm for the IR channel. It will be possible to select spectral ranges over which spectral binning will not be implemented, providing up to 640 spectral samples after selective spectral binning. The design of the electronics has been updated and simplified, with all electronic elements now implemented as a single module. Specific on-board processing procedures have been developped for improving data quality by limiting the impact of « spikes » generated by high energy electrons to at most 1% of the data elements. Updated performances for the major goals of MAJIS (surface of icy satellites, atmosphere of Jupiter, exospheres, small satellites and rings…) will be presented. The updated MAJIS design makes it possible to meet the objectives defined for MAJIS in the Science Requirement Document of the JUICE mission