Exogenic versus endogenic features of the planetary satellites

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Overview. A primary tool for studying icy bodies in the solar system is optical remote sensing. One focus of that research is inferring surface composition, since that may yield important clues about the formation and evolution of planetary satellites. In general, researchers can typically probe the very top layer of the surface (down to a mm or so) by these means. However, the uppermost part of a surface is typically exposed to solar UV, cosmic rays, and a local environment of plasma, energetic charged particles, and dust (cometary and other forms). Two processes that are important for this discussion are, additions to the surface (e.g., material from sources like Io's volcanoes that reach other bodies and solar wind ions) and weathering of the surface (e.g., physical and chemical changes as described in Johnson et al. 2004). Here, the latter includes all external driving such as sublimation and sputtering, and dust and cosmic ray impacts.

The question then is, how can the composition of pristine materials be inferred? An example of the difficulty of such an analysis is material from a putative Europa plume that immediately begins to be altered once it is on the surface and exposed to Jupiter's harsh radiation environment. While the past decade has devoted a great deal of research toward identifying surface constituents, the coming decade must go further and understand whether these are connected to internal or external processes. This information will help prepare for future missions to these bodies such as, JUICE (ESA) and the Europa Clipper (NASA). In sections below, we discuss open questions and recommendations.

Radiation environments of planetary satellites. The radiation environment a moon is exposed to depends on many different factors, primarily its location in the magnetosphere of the parent planet. In the inner regions of the magnetosphere, where magnetic field lines are closer to a dipolar configuration, quasi-stable trapping of charged particles leads to the formation of highly energetic radiation belts. These particles pass through patchy atmospheres into the surface.

In addition to the location of the moons, the dynamics of the parent planet's magnetosphere also play a significant role. The ionosphere enforces a corotation of the magnetosphere with the planet at a speed that is significantly larger than the Keplerian orbital speed of the moons at Jupiter and Saturn. This creates an asymmetric precipitation pattern, where the trailing hemispheres of the moons are constantly bombarded by the corotating plasma in many cases. This is true for ions and most electrons. However, electrons with energies above a resonant energy, where the gradient-curvature drift causes a net reversal of the longitudinal motion (Thomsen and Van Allen 1980), have preferential access to the leading hemisphere of the moons (Paranicas et al. 2014).

The presence of sub-surface oceans within Jovian and Saturnian moons has been inferred, for example, from magnetic induction signals detected with *in situ* magnetic field measurements. In addition, satellite ionospheres act as an obstacle to the plasma, creating in turn a draping pattern in the magnetospheric magnetic field. Both signals affect the precipitation of particles, further complicating the interaction of the magnetospheric plasma with the surface. Furthermore, Ganymede is believed to be partially shielded at low latitudes from the direct bombardment of corotating plasma by its intrinsic magnetic field (e.g., Khurana et al. 2007).

Finally, the precipitation pattern onto a moon also depends on a combination of the particle's gyroradius, the pitch angle distribution of the incoming plasma and particles, and the equatorial displacement between successive latitudinal bounces of those particles. All of this combined creates a complicated picture that makes it difficult to quantify the effects of precipitating charged particles onto the surfaces of these moons. Multiple simulation studies have addressed this issue at different moons using different approaches (e.g., Cassidy et al. 2013; Regoli et al. 2016), but only *in situ* measurements can provide an accurate view of the dynamic plasma environments and how these affect moon surfaces.

These same processes are even less understood for the moons of the ice giants. With the Voyager 2 flybys more than 30 years ago, the lack of *in situ* data makes it difficult to provide realistic constraints to any model to study the precipitation of charged particles onto the ice giant satellites. In addition, Uranus and Neptune have large tilts between their principal magnetic dipole and spin axes, complicated further by obliquity (Bagenal 1992). These particular configurations are expected to provide much more complex interactions than the ones observed at Jupiter and Saturn, with different bombardment patterns taking place in different seasons.

Water ice. Water ice is a common constituent of surfaces in the outer solar system. In the Saturnian system, one hypothesis is that water ice from Enceladus's plumes coats the nearby satellites, making them brighter because the ice is fresh (e.g., Buratti et al. 1990; Hamilton and Burns 1994). The Jovian satellites are more complicated. Io is covered with SO₂ frost, due to

Figure 1. From Grundy et al. (2007) depicting non-ice distributions on Europa derived from New Horizons spacecraft data. The trailing apex is located at 0° latitude and 270° W longitude.

active volcanism. Europa, Ganymede, and Callisto are icy but have significant amounts of other materials, sometimes collectively referred to "non-ice" compounds (see Figure 1). Moore et al. (2004) cites research suggesting water ice is the dominant component on the surfaces of Europa and Ganymede and that heavily hydrated non-ice salts or acids are also prevalent. Callisto's spectra suggest the moon's surface is dominated, not by water ice, but by a less hydrated assemblage of non-ice minerals, such as phyllosilicates (Calvin et al. 1995).

For the Jovian satellites, the water-ice is very heterogeneously distributed, with a clear latitudinal gradient. Moreover, for Europa, a strong hemispherical dichotomy is observed where the apex of the trailing hemisphere is the most water-ice depleted area on the surface, very likely because of sputtering of the ice due to ions that move with the corotating plasma (e.g., McEwen 1986; Baragiola et al. 2013). A similarly located water-ice depletion seems to exist on Ganymede, but it is much weaker (Ligier et al. 2019). This suggests two things: (1) the more plasma/energetic particles, the stronger the water-ice depletion, and (2) singly charged corotating ions could be neutralized and pass into the surface even if there are electromagnetic fields above the body, such as at Ganymede, and still sputter the ice. These observations suggest the following

questions: What are the non-ice materials on the three outer Galilean satellites? Are they lag deposits in sputtered and/or sublimated areas? Are they internal/external materials?

Species. A longstanding discussion about Europa is the nature of the non-ice. These materials have been considered as salts, suggesting they have an internal origin, and acids, suggesting that materials from the outside that are incorporated into the ice. Fortunately, excellent Earth-based data is now available so that some solar system bodies are accessible spectrally (e.g., Ligier et al. 2016). Important trends in the Jovian system are materials such as sulfuric acid and polymeric sulfur (Carlson et al. 2009), CO₂ and SO₂ (Hibbitts et al. 2000), Mg-bearing (Ligier et al. 2016) or Na-bearing chlorinated salts (Hand and Carlson 2015; Trumbo et al. 2019), and peroxide. Some of these have been interpreted as markers of subsurface oceans (Hand and Carlson 2015). With future missions scheduled to visit the icy satellites of Jupiter, we believe a major thrust in the coming decade should be laboratory studies (more below) that can complement *in situ* work and remote observations (at least between the UV and the thermal IR).

Another source of ion species is the solar wind itself. It is dominated by protons and helium with trace amounts of other ions (e.g., Mg, Si, Fe). The penetration of the solar wind into magnetospheres can come about in a number of ways, e.g., by reconnection at the magnetopause. But solar wind entry processes are not well quantified. Combined with the long timescales on which these processes take place, it is not clear, for example, how much solar wind iron ends up on any satellite or how that iron is processed and incorporated into the regolith.

Lastly, new species may be delivered to satellite surfaces by the action of cosmic rays (CRs). These are unique species and they are mostly not impeded from reaching the planetary satellites directly. Hedman (2019) has pointed out that when CRs impact surfaces their nuclear reactions generate lighter nuclei than the original CR. He goes on to describe how this process can be used to date surface layers in the future (Swindle et al. 2005).

Ice state. Water ice itself can be a weathering product. Hansen and McCord (2004) showed that the Galilean moons contain quantities of amorphous ice that are correlated with their proximity to the most intense portions of the Jovian radiation belts. Most of the water ice in the outer solar system is in the crystalline state. Ligier et al. (2016) also found a compelling separation of amorphous and crystalline ice on Europa. That work and others illustrate the power of remote observations on solar system bodies to understand detailed structure. Zheng et al. (2009) showed energetic electrons can modify surface ice (crystalline to amorphous) at cold temperatures (below ~50K). Many laboratory studies (see summary in Mastrapa et al. 2013) have experimented with ions to create the transition from crystalline to amorphous at temperatures typical of the surfaces of Europa, Ganymede, and Callisto. It is therefore possible to use remote sensing of solar system objects to infer their local environments. There are still many open questions, because of the various pathways to each ice state (e.g., deposition of plume material as discussed in, Newman et al. 2008; Mitchell et al. 2017).

Regolith structure. Another important subject for planetary moons is compactification. There are different ways the geophysical properties of the regolith can be altered. Schaible et al. (2017) have investigated how grain contacts change if free energy is added into the system. More empirically, Schenk et al. (2011) have shown examples of a trailing hemisphere bull's-eye on the

Saturnian satellites, likely due to the action of the cold plasma. Howett et al. (2011) have hypothesized that energetic electrons may form thermally anomalous regions on the leading hemispheres of some Saturnian satellites, possibly due to sintering of the grains. The leading hemisphere of Europa is also anomalous, possibly due to bombardment by tens of MeV electrons, and bears further investigation. Hedman et al. (2020) have suggested that, while the brightness of the inner Saturnian satellites might be correlated with their proximity to Enceladus as previously reported, deviations from the pattern might be explained by energetic charged particle modifications of the surface.

Dust. Dust has many sources and its composition is often a mystery. Dust grains can be thought of as fine grains and larger grains. Very small grains are strongly influenced by electromagnetic forces and in magnetospheres can be expected to move like the cold plasma. That is, they would preferentially flow over satellites encountering the trailing hemisphere first. Larger grains are more complicated because gravitational forces play a more important role in their motion. Hamilton and Burns (1994) showed that grains launched from Enceladus would asymmetrically coat the Saturnian satellites (see their footnotes). Dust interacts with plasma (e.g., Simon et al. 2015) and adds a composition that may not be indigenous to the bodies (e.g., Krüger et al. 2003; Postberg et al. 2018). By accounting for its bombardment patterns, it might be possible to rule in/out some species as exo/endogenic. In addition to its multiple sources, a complicating factor is modeling the dynamics of dust if multiple forces are at play. Finally, surface impacts (dust or larger) have the potential to expose material below (Verbiscer et al. 2007).

Bombardment. We have noted some issues of bombardment above, e.g., cold plasma preferentially flows onto trailing hemispheres in the Jupiter and Saturn systems. But bombardment as a process for altering existing non-ice constituents or contributing new constituents has been studied only in a limited sense. Some very coarse estimates of fluxes into surface regions have been carried out assuming the satellites are inert bodies (Paranicas et al. 2014) and other studies have investigated the effect of an inhomogeneous electromagnetic field environment on bombardment patterns of energetic particles (e.g., Breer et al. 2019; Liuzzo et al. 2019). However, more work is needed. Important complicating issues include wave-particle interactions that can alter the fluxes of particles near surfaces (e.g., Nénon et al. 2018). Particles-and-fields instruments, either on the surface or near the body that detect precipitating particles, would greatly enhance our knowledge of these processes.

Destruction of molecules. There has been recent interest in missions to the surface of icy bodies such as Europa (Pappalardo et al. 2013; Hand et al. 2017). Such missions would utilize *in situ* sampling to investigate potential endogenic material, and perhaps even search for biosignatures within. However, endogenically sourced molecules brought to the surface could eventually become chemically modified and destroyed by incident charged particle radiation. Such alteration could obscure, or even erase, the chemical fingerprints of the original material (and any biosignatures it contains). Therefore, any future mission that seeks to sample “pristine” unaltered material would need to retrieve samples below the radiation-processed uppermost surface layers. On Europa, Nordheim et al. (2018) found that amino acids within the top cm to tens of cm would be heavily degraded by radiation from Jupiter’s magnetosphere. Figure 2 shows an estimate of the time (yrs) to reach a significant ionizing dose (100 eV per 16 amu) at a range of surface depths. Similar assessments would need to be made for future *in situ* surface

missions to other bodies, including possible Ocean Worlds such as, Ceres, Ganymede, Callisto, and Enceladus (Hendrix et al. 2019).

Figure 2. From Nordheim et al. 2018, showing the timescales for the accumulation of significant radiation dose at varying depths at the surface of Europa.

Related questions for the next decade.

- What is the composition of the non-ice materials on Europa, Ganymede, and Callisto?
- Are younger surfaces more likely to contain crystalline ice?
- What processes account for the current amount of water ice on moon surfaces?
- Is there a substantial amount of amorphous ice on any outer solar system

bodies besides Europa and Ganymede?

- What processes can we use to infer pristine material composition from the weathered version we encounter on these surfaces?
- What regolith types do we find on the planetary satellites, how do these types emit light, what do they tell us about the evolution of the body?
- How can we quantify the effects of solar wind material reaching satellite surfaces?
- What materials do dust particles bring to icy bodies and where are they distributed?

Recommendations.

We advocate for more laboratory simulations of exogenous processes affecting icy satellite surfaces, e.g., spectral absorptions of weathered salts are detected on Europa, especially sodium chloride (Hand and Carlson 2015, Trumbo et al. 2019).

We support more ground-based observations of planetary satellites. The upcoming IFS of the future E-ELT observatory (HARMONI, METIS) will provide a spatial sampling close to 10x10 km of the Galilean moons. Also, ALMA. These are critical studies.

In addition to supporting more studies as in the previous note, we believe novel Earth-based observing campaigns are important.

In situ instrumentation to constrain what is bombarding the moons, where, and with what flux. The main instruments are: magnetometers, plasma devices with species and charge state knowledge, charged particle and dust detectors, with species knowledge when possible.

Continue to analyze light emitted from surfaces over a wide range of wavelengths, including continuous surface monitoring at thermal and microwave (e.g., Clipper/E-THEMIS).

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