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The Next-Generation Laboratory Experiments on Planetary Materials

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Abstract. Laboratory experiments are found to be extremely important in the field of planetary and exoplanetary science. In this proceeding, I cover three aspects of my envisioned next-generation laboratory research and the previous and current works of our group on achieving these visions. I will include three topics: 1) using material science techniques to study planetary materials, 2) collaborative laboratory research on planetary and exoplanetary haze analogs, and 3) building a robust laboratory database to better understand various atmospheric and surface processes on Titan and exoplanets. I will also elaborate on how such laboratory work could power next-generation space missions such as the Dragonfly mission to Titan and the James Webb Space Telescope.

Keywords. Titan, Exoplanet, Planetary material, Material Characterization, Laboratory Astrophysics

1. Introduction

The fields of planetary and exoplanetary science have seen tremendous growth in the past few decades. Within the Solar System, the Cassini-Huygens mission conducted a grand tour of the Saturnian system for 13 years, in particular, exploring Saturn's enigmatic moon, Titan. The New Horizons mission explored the farthest former planet (Pluto) in the Solar System and a Kuiper Belt Object, Arrokoth. In the next couple of decades, we will go beyond orbiters and landers – NASA's Dragonfly mission will explore the surface of Titan through a rotorcraft lander in the 2030s (Barnes et al. 2021), and various sample return missions are bringing extraterrestrial samples back to Earth from asteroids, Mars (Lauretta et al. 2017; Watanabe et al. 2017; Murakami et al. 2020), which opens unprecedented pathways to explore materials beyond what we have on Earth.

The exploration of planetary bodies does not stop at the farthest planet in the Solar System. We have detected over 5000 exoplanets to date. We are exploring sibling systems that do not look like our Solar System, with scorching hot Jupiter-sized planets orbiting close to their star and enigmatic sub-Neptunes with sizes between Earth and Neptune. The latter being the most common type of exoplanets detected so far (Fulton & Petigura 2018). In the next coming decades, beyond characterizing rudimentary properties such as mass, size, and orbital parameters of these exoplanets, we are entering a new era of exoplanet characterization with the next-generation powerful space telescopes such as the James Webb Space Telescope and the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) telescope. We will be able to probe the molecular constituents in the atmospheres of these exotic worlds and start to assess planet evolution and habitability beyond our Solar System. Our limited data from the Hubble Space Telescope have already revealed a diversity of exoplanet atmospheric properties. The large phase space of conditions on exoplanets thus opens another pathway to investigate the principal of atmospheric physics and chemistry and the diverse range of materials that could exist on these bodies.

In this proceeding, I would like to discuss how planetary material research will play an important role in enhancing the scientific return of these missions within and beyond the Solar System. I will summarize the progress and prospect of planetary material research for Solar System bodies, focusing on Titan and existing and upcoming sample return missions. I will then discuss how planetary material research can benefit the exoplanet field. Even though the exoplanetary materials are not accessible as solar system materials, their properties indeed exemplify in observations that are accessible. Lastly, I will emphasize the link between planetary and exoplanetary material research and how collaborative planetary material research can readily benefit future exoplanetary material research.

2. Planetary Material Research for Solar System Science

Planetary materials are essential components to understanding various processes on planetary bodies. The materials on terrestrial planets are dominantly silicates, while the materials on outer solar system bodies are dominantly organics and ices. While small bodies have materials that are a combination of those of terrestrial and icy bodies. The "traditional" planetary material properties that are studied extensively are their chemical composition and optical properties. Chemical compositions are important as mass spectroscopy has become the standard instrument to send on space missions in the Solar System. Optical properties of planetary materials are important to interpret both ground-based and space-based spectroscopic observations. The increasing amount of space missions that perform in-situ measurements (landers, rovers, and drones) and return samples to Earth for analysis allows us to investigate more properties of planetary materials.

2.1. *Novel material science techniques to study planetary materials*

Many planetary surface and atmospheric processes are the results of a combination of the dynamical environments and the properties of the local planetary material. Take Titan as an example, there are many puzzles regarding the equatorial dunes seen on Titan's surface (Barnes et al. 2015). One could investigate how the dune formation processes are affected by the unique environmental properties on Titan (low gravity, high atmospheric density, and weak winds, e.g., Burr et al. 2015). On the other hand, Titan's surface sediments are dominantly made of organics sedimenting from Titan's atmosphere, and the properties are the surface sediments also play a strong role in shaping the dune formation process.

As an example, the surface properties (or the cohesion) of the sediments would determine how much wind is needed to mobilize them, the mechanical properties of the sediments would affect their transport capacity (mechanically weak sediment would be abraded to dust quickly that ceases their mobility for further transport), and the electrical properties would affect the trajectories of sediments and the final dune form if the sediments can be electrically charged during transport. Novel material techniques developed in the past few decades allow us to investigate these properties, even given very small amounts of materials. I have been using some of these techniques, including colloidal atomic force microscopy and nanoindentation, to measure the surface, mechanical, and electrical properties of typical sediments on Earth and Titan regolith analogs (Yu et al. 2017, 2018, 2020a,b). These studies suggest that the organic-rich Titan sediments behave very differently than silicate-rich terrestrial sediments. The Titan sand is likely more cohesive, mechanically much weaker, and barely produces any electrical charges with friction. All these properties have significant implications for sediment transport on Titan. Given the sediment's larger cohesion, a higher wind speed is needed than previously thought to mobilize the sediment through direct fluid drag. This has direct implications on how/when the sediments are transported to form the dunes (Comola et al. 2022). Given the sediment's weak mechanical properties, they can hardly sustain long-distance transport as silicates sand on Earth before being abraded to dust, this helps us narrow down formation pathways of the sediments (i.e., they have to form close to where they are located currently, Yu et al. (2018) and shed some light on the nature of Titan's most mysterious terrain, the mid-latitude blandlands or the undifferentiated terrain (Lapôtre et al. 2022). Given the weak electrical charging properties of the Titan sand compared to Earth sand, we think electrical forces do not play a dominant role in governing sediment transport on Titan (Méndez Harper et al. 2017; Yu et al. 2020b).

It may seem these material properties are not readily measurable through space missions. But given the capacity of future spacecrafts that are able to perform in-situ investigations, some of the properties are indeed accessible. For example, the Huygens probe, when it landed on the surface of Titan, measured the mechanical properties of the surface sediments with a penetrometer at the bottom of the spacecraft. The Dragonfly mission will also be able to survey the mechanical properties of the sediments. Even though the direct comparison between the penetrometer data performed by the spacecraft (which is performed on large amounts of sediments) and the mechanical property measured by nanoindentation (which is performed on a single-particular level) remains difficult, the measured nanomechanical properties have allowed us to produce a Titan regolith simulant in large quantities, which would then enable direct comparison to spacecraft data (Brisset et al. 2022).

The sample return missions, however, would fully enable the necessity of these material property measurements. Most of the existing and planned sample returns come from small airless bodies, where environmental-induced forces (gravitational force, wind-induced drag force) typically remain weak, due to the weak gravity and minimal atmospheric pressure. Thus, the interparticle forces dominate over these environmental-induced forces on small airless bodies, and the interparticle forces are heavily affected by the material properties of the surface sediments. This underscores the importance of characterizing various material properties that would shape the force environment of sediments on small bodies. Because of the small amount of available returned samples, nanoscale and single-grain level measurements would be the most suitable techniques to characterize their material properties.

2.2. *Collaborative laboratory research on planetary materials*

So far, the most abundant materials available that originated outside Earth are meteorites, which have a great catalog system that allows comparison studies. Meanwhile, we do not have returned samples for most extraterrestrial bodies, especially for outer solar system bodies, where return samples will not be available in the near future. Thus, laboratory simulations that produce analogs of planetary materials remain the main way for us to understand these materials and their properties.

For the organics on Titan, laboratory simulation experiments that produced Titan's aerosol analog, the so-called "tholins", started a few decades ago in the 1980s (Sagan & Khare 1979). Various laboratory groups have attempted to simulate tholins with their

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own experimental setups that are accompanied by a range of experimental conditions mimicking Titan's energy environment. Previous studies from individual laboratories have suggested that tholins are decent analogs to the actual Titan aerosols as their chemical and optical properties match, at least partially, the Cassini-Huygens observations (see references in Li et al. 2022).

However, to date, there have been few studies to compare the different tholin samples made in different laboratories (Coll et al. 1999; Cable et al. 2014). Prevailing questions remain on whether and which these laboratory-produced analogs best represent the actual aerosols on Titan. In addition, the selected properties measured in individual laboratories often came from different measurement techniques performed under different environmental conditions, thus, it is uncertain if the data from the literature are directly comparable. To solve these discrepancies, we initiated an effort to conduct collaborative laboratory research among different tholin production facilities, and our pilot study was recently published as Li et al. (2022), where seven tholin samples from three individual facilities are used for direct comparison. In Li et al. (2022), we choose to measure an important material property that is relevant for atmospheric and surface processes such as cloud formation and aerosol-lake interactions on Titan, the surface energy. We found that the tholin samples produced in different laboratories have varying surface energies. We identified the key experimental condition that dominantly controls the surface energy of the tholin, which is the energy source used to initiate the chemistry. The energy source seems more important than other experimental parameters, such as temperature, pressure, and gas exposure time. Samples produced by the same energy source tend to have similar surface energy values despite the differences in other experimental conditions. The samples also have some commonality – all the samples seem to have a high dispersive surface energy component, despite the different setups/conditions that are used to produce them. This pilot comparative study allows us to provide a reasonable range of surface energy values for the community to use for atmospheric and surface models, which considers the variability of the tholin properties.

We are continuing this collaborative approach to studying tholins by employing a standardized characterization plan. All laboratories would receive identical substrates for the deposition of the samples. After sample production, all laboratories would follow a standardized transportation and storage pipeline that minimizes sample contamination by the ambient atmosphere. Finally, all samples will be characterized by the same standardized measuring facility in an inert atmosphere. This approach allows us to confidently compare the properties of the samples. By employing this approach to study properties accessible by previous or future missions on Titan, we hope to identify the key experimental conditions that control the property of actual haze particles and organic surface sediments on Titan.

2.3. *Planetary material property database*

We know that a diverse range of planetary materials can exist in the atmosphere and on the surface of various planetary bodies: from silicate rocks to various liquids or ices that condenses at different temperatures across the Solar System, and simple and complex organics that are either primordial or produced by chemical processes. Most of these materials actively participate in various planetary atmospheric and surface processes, and we need to have access to their material properties to be able to characterize the various processes they are involved in. This underscores the importance of establishing a property database that is dedicated to planetary materials that are easily accessible by the community.

On Titan, the planetary body with the richest inventory of planetary materials in the Solar System, a variety of simple organics have been detected in its atmosphere and can be present in various phases (gas, liquid, solid) at different altitudes, latitudes, and seasons on Titan. There are also the complex organics that form Titan's thick haze layers, which are simulated in the laboratory as the analog "tholins". We have compiled the first material property database that is dedicated to the materials on Titan. The database summarizes relevant thermodynamic, physical, surface, optical, and electrical properties for atmospheric and surface models (Yu et al. 2022). The simple organics data are compiled from over a hundred years of data in the literature and the complex organics data are compiled from existing tholin measurements and the collaborative comparison study in Section 2.2. Many of these properties are also applicable to giant planets and icy bodies in the outer solar system, interstellar medium, protoplanetary disks, and exoplanets. We are hoping to continue updating and compiling such planetary material databases for the community for Titan and beyond.

3. Planetary Material Research for Exoplanet Science

Similar to planets in the Solar System, planetary materials are also essential elements of exoplanetary science. The potential materials that exist on exoplanets span across even a larger phase space than Solar System materials, with temperature spanning from > 3000 K for hot Jupiters, down to cold habitable planets and cooler objects. Under equilibrium chemistry assumptions, a range of species can condense at these different temperature conditions to form clouds (Zhang 2020). Chemistry can also happen in various types of atmospheres with different temperatures and atmospheric molecular compositions, leading to the formation of refractory hazes. Aerosols, including clouds and hazes, are found to have a large impact on the observed transmission spectra of exoplanets, impeding us from detecting signals from atmospheric molecules. The production of refractory hazes has some habitability implications, as the haze particles would eventually fall upon the surface of an exoplanet (if it has one). The rich organic compounds in the hazes could at least provide some initial organic matter for life to brew on (e.g., Moran et al. 2020). Some observations may even have the potential to directly probe the composition and particle size distribution of exoplanet aerosols, such as reflected light observations, the polarization of reflected light, and thermal emission observations (Gao et al. 2021). In addition to planetary atmospheric molecules, recent thermal emission observations also have to potential to reveal the composition of the bedrock of atmosphere-free planets (e.g., Kreidberg et al. 2019).

Many observations would require knowledge of the material properties of relevant materials at exoplanet-relevant temperatures and pressure conditions. For example, the optical properties of many of the high-temperature condensates and photochemical hazes are not well constrained. Recent laboratory experiments have shown that other material properties of the aerosols, such as the surface properties would also affect the evolution of aerosol particles in exoplanet atmospheres and may determine the overall haziness/cloudiness of an exoplanet (Yu et al. 2021). More laboratory experiments are needed to fully understand the impact of aerosols in planetary atmospheres and ultimately the key physical conditions and chemistry that determine the observed condition of exoplanet atmospheres.

4. Synergy between Planetary and Exoplanetary Material Research

In our Solar System, planetary materials mostly exist under conditions <1000 K, while exoplanetary materials can undergo conditions over a couple of thousands of Kelvins. The currently observable exoplanet systems typically have equilibrium temperatures beyond

200 K. However, Solar System material research can still benefit the understanding of exoplanetary materials through the infrastructure that is already or being built to study planetary materials. As an example, the comparison study that is being conducted for Titan aerosol analogs is readily applicable to studying exoplanetary hazes. Given that we have more observations of Titan's aerosols, we can use the existing observational data and laboratory data to better understand which experimental conditions better reproduce the Titan hazes in the laboratory and the impact of various experimental conditions on the properties of the aerosols. The comparison study can also be extended to study hazes on exoplanets of particular interest. The infrastructure to build the planetary material database is also extendable to exoplanetary materials – where a survey of existing data can be conducted and then fill in the gaps through further laboratory work.

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