TRITON ICES MAPPER: A VNIR SPECTROMETER FEASIBILITY STUDY.
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Introduction: With increasing opportunities to propose missions to the outer Solar System [1, 2], science and engineering teams are exploring the measurement and detection limits of the instruments such missions would carry. Beyond the Saturnian and Jovian systems are several moons, the study of which will answer key science questions about our Solar System and the diversity of planetary bodies it contains. With technological advances, we may, at last, begin to develop missions that will map the surface compositions of these bodies.

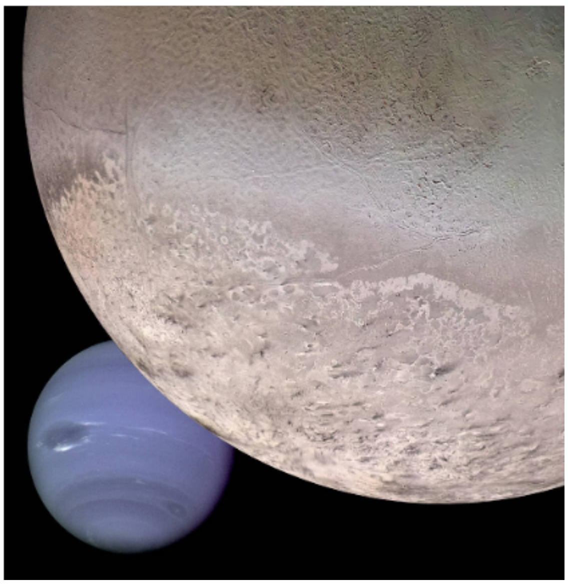

Figure 1: Triton and Neptune (Voyager 2 [3]).

Neptune's moon, Triton, is a unique body in the outer Solar System. At 30 AU, Triton has a surface temperature that, at ~38 K, is among the coldest in the Solar System [3]. Among its characteristics are a suspected subsurface ocean [2], potential cryovolcanic features and active plumes (detected by Voyager 2 in 1989 [4], Figure 1), and a geologically young surface [5]. One of Triton's interesting characteristics is its origin. With its peculiar retrograde orbit, it is thought to be a captured Kuiper Belt Object (KBO) [6]. As one of the closest potential KBOs, Triton is our key to understanding the objects that exist in the far reaches of our Solar System.

Triton has been identified as the highest priority candidate ocean world in *Roadmaps to Ocean Worlds* [7], and numerous science questions highlighted Triton in the last Decadal Survey. *Vision and Voyages for Planetary Science in the Decade 2013-2022* poses one particularly interesting scientific question: "What geologic processes operate on Triton's unique surface?" [8].

Here, we investigate the feasibility of a spectral mapping instrument to orbit Triton based on planned future missions (e.g., [1]) to other outer Solar System moons. The Moons And Jupiter Imaging Spectrometer (MAJIS) is part of the instrument suite on board JUpiter Icy Moons Explorer (JUICE), launching in 2022 [1]. We outline the instrument concept and performance model of a MAJIS-like spectrometer with the intention of achieving our science goal to understand the composition of Triton's subsurface ocean and how it expresses itself on the surface. In more detail, our science objectives are to constrain the processes which relate to and/or cause resurfacing on Triton and to develop an understanding of the spatial distribution of Triton's surface composition.

Background: Ammonia (NH_3) has been recently detected on other possible KBO objects [9] using near-infrared spectroscopy. When mixed with liquid water, NH_3 acts as an antifreeze, lowering the freezing point of the material. Coupled with Triton's high inclination and obliquity, sufficient NH_3 detected on Triton could be a possible indicator of a subsurface ocean on Triton [2]. Solid ammonia has two major IR bands in our proposed spectral range: one centered at 2.2 μm and one at 2.0 μm. The band at 2.2 μm is a reliable indicator for the presence of NH_3, but the chemical concentration is difficult to determine.

CH_4 ice produces many strong absorption bands in the near-IR. In previous studies by Grundy et al. [10, 11], bands at 0.89, 1.15, and 1.33 μm were most successful at detecting variations in CH_4. It has been determined that Triton's CH_4 is diluted by N_2 ice by the blue shift of certain CH_4 bands [11]. If there is difficulty resolving the N_2 band at 2.15 μm, the detection of this blue shift can be used to infer the presence of N_2.

CO_2 has absorption bands at 2.01, 2.07, 1.96, and 1.58 μm. The strongest and most used band in planetary remote sensing is at 2.01 μm [10].

While there are many H_2O bands in the near IR range, the strongest are at 1.5, 1.89, 2.0, and 3.0 μm [10]. The wavelength 1.89 μm has the least contamination from other molecules and will be predominately used in this study.

VNIR Instrument Concept: Grundy et al. [10] found that there are both spatial and temporal variations in the ices on Triton's surface, so to constrain the composition of Triton's surface and to achieve our science objectives as outlined in the introduction, an orbital detection system is suitable. Given the range of wavelengths (0.5 - 3.5 μm) necessary to compositionally map and differentiate Triton's surface, the visible to near infrared (VNIR) is the most appropriate spectroscopic range for detecting ices on Triton's surface.

An instrument designed for a Triton orbit will have to account for Neptune's radiation field. The total ionizing dose rate in the 14th L-shell (Triton's orbital band) is on the order of 10^{-7} rad(Si)/s, which would be an insignificant amount even after 100 days of orbit [12]. According to the JPL Neptune Radiation Model, if 100 mil aluminum shielding is applied to the detector, radiation should not be a concern in the region outside of 10 Neptunian radii [12].

An atmospheric correction will not need to be applied as the chemical makeup of Triton's atmosphere does not absorb a significant amount of signal in the relevant wavelength range [13].

The technology flown on JUICE is designed to withstand Jupiter's harsh radiation environment and will focus on potential ocean-bearing bodies, Callisto, Ganymede, and Europa. These mission goals could align with a mission to Triton, so design specifications in this feasibility study utilizes MAJIS' optical parameters [1, 14].

Instrument Performance Model: At 30 AU from the solar energy source, the proposed spectrometer will need to detect signal reflected from Triton's surface. However, Triton's surface is composed of ices that reflect 70% of the light that reaches the surface [15]. The spectral radiance of the Sun and the solid angle of the Sun was computed and used to calculate the spectral irradiance at the target. Triton's reflected radiance was calculated in units of photons $\times$ m^{-2} $\times$ μm^{-1}. The minimum reflected radiance of 6.5×10^{16} occurs at 3.5 µm, and the maximum reflected radiance of 1.2×10^{18} occurs at 0.64 µm.

In calculating the signal-to-noise ratio (SNR) of a MAJIS-like detector in the Neptune system, we considered three noise sources: Read noise from electronics within the detector, thermal emission from the instrument, and dark current, which is the process of thermal agitation dislodging electrons. Using MAJIS specifications in our SNR calculations, we set an initial SNR requirement of ≥100:1. However, that requirement was solely met below 1 µm at 0.1 second integration time (Figure 2), and below 3 µm at 1 second integration time. Available signal requires longer integration across our 0.5 - 3.5 µm wavelength range but must be reconciled with the instrument's orbital motion and required spatial resolution. To maintain a shorter integration period, photons will need to be collected through alternate techniques including multiple passes over a single location or time-delay and integration (TDI).

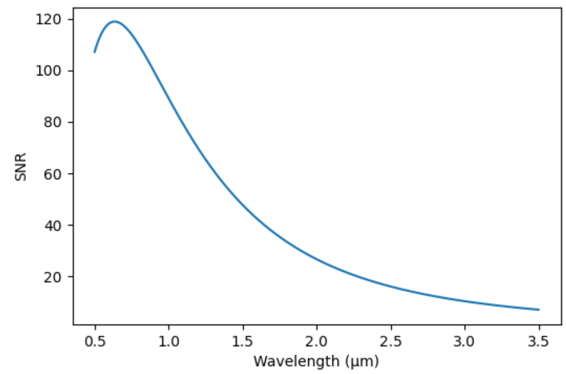

Figure 2: Variations in SNR with wavelength at 0.1 second integration.

Conclusion: The Triton orbiter outlined in this feasibility study, which features a visible to near-infrared spectrometer, is designed to expand our understanding of the existence and composition of a possible outer Solar System subsurface ocean and explore how that may change our current definition of our Solar System's habitable zone. Through remote sensing of the ices which comprise the geologically young surface (N_2, CH_4, H_2O, NH_3, CO_2, and CO), we may begin to construct an explanation for the active geologic resurfacing processes occurring on Triton.

The performance modeling exercise demonstrates that the chemical composition of Triton's surface can be measured using a MAJIS-like VNIR instrument. Some adaptations to the instrument and measurement procedures are suggested. The measurements made by this instrument will help further our knowledge of the origins of KBOs and their behavior as satellites. A study of Triton's unique surface geology offers insight into the properties of many planetary bodies at the far reaches of our Solar System that are otherwise inaccessible due to current technological limitations. It is our hope that a visit to Triton will provide valuable scientific insight towards understanding the diversity of our Universe.

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