ARTICLE IN PRESS

Planetary and Space Science xxx (2017) 1–9

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Cold cases: What we don't know about Saturn's Moons

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ABSTRACT

The *Cassini*-Huygens mission turned the moons of Saturn into tangible worlds. Although the discoveries from the spacecraft have been compiled in various review articles (e. g., Dougherty et al., 2009), there is no single publication that summarizes the remaining outstanding questions. Drawing on a workshop sponsored by the *Cassini* Project, we summarize the unanswered questions for the main icy moons of Saturn – Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Iapetus, and Phoebe - for the disciplines of surface composition, geology, thermal properties, Enceladus's plume activity, interiors, and the interactions between Saturn's magnetosphere and the moons.

1. Introduction

The *Cassini*-Huygens mission offered the first extended, comprehensive view of the moons of Saturn. There are existing and upcoming review books and papers that summarize the results from the *Cassini* mission; for icy moons there is Dougherty et al. (2009). As is the case with so many previous missions, major questions remain even after more than a dozen years of exploration. The purpose of this paper is to review some of the open questions regarding icy satellite investigations in specific areas, including surfaces, interiors, and magnetospheric interactions. Beyond the questions appropriate to each discipline, this paper examines the status of the far-reaching science goals that were posed at the beginning of the mission and drove it (Spilker, 1997):

1. Determine general characteristics and geological histories of satellites
2. Define mechanisms of crustal and surface modifications, both external and internal
3. Investigate compositions and distributions of surface materials, particularly dark, organic-rich materials and low-melting-point condensed volatiles
4. Constrain models of satellites' bulk compositions and internal structures.
5. Investigate interactions with Saturn's magnetosphere and ring system and possible gas injections into the magnetosphere

All these objectives have been answered to a large degree, but specific questions remain, and major discoveries spawned additional questions such as what is the nature, source, and variability of the activity on Enceladus? Are Dione or other moons active now or in the past? What are the thermal properties of the moons?

This review covers the main scientific questions that remain for the icy major moons of Saturn: Mimas, Enceladus, Tethys, Dione Rhea, Hyperion, Iapetus, and Phoebe. A companion paper (Nixon et al., 2017) covers “cold cases” for Titan.

2. Surface composition of the moons

Identifying and mapping the components of the moons' surfaces was one of the primary goals of the *Cassini* mission. This goal has been largely met, but the identity of minor constituents is still in question and there is unexpected complexity to some surface materials. Ground-based observations identified crystalline water ice as the major constituent of the surfaces of the main moons of Saturn (see review in Cruikshank et al., 2005). The *Cassini* Visible and Infrared Mapping Spectrometer (VIMS) confirmed this view but not without ambiguity since the reflectance spectrum of water ice can be quite complex. Besides varying with temperature (e.g. Mastrapa et al., 2008, and references therein), the water ice spectrum varies with grain size and contaminants (e.g. Clark, 1981a, 1981b, Clark et al., 2012, 2013 and references therein). Early results on

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https://doi.org/10.1016/j.pss.2017.11.017
Received 31 May 2017; Received in revised form 4 October 2017; Accepted 28 November 2017
Available online xxxx

Please cite this article in press as: Buratti, B.J., et al., Cold cases: What we don't know about Saturn's Moons, Planetary and Space Science (2017), https://doi.org/10.1016/j.pss.2017.11.017

Enceladus (Brown et al., 2006) suggested the existence of amorphous ice due perhaps to quenching of water icy particles from its plume, but further work showed that if grain size was varied, crystalline ice could explain all spectral signatures (Clark et al., 2012).

Are high pressure ice phases present? Gafney and Matson (1980) argued that high pressure polymorphs of ice, e.g. created by meteor impact, could be stable on cold icy satellite surfaces. To date, only crystalline ice has been definitively detected. However, reference laboratory spectra of some high pressure ices are lacking.

Some species have been definitively detected: for example, CO_2 is present on the surface of most of the moons (Buratti et al., 2005; Brown et al., 2006; Clark et al., 2005, 2008, 2012, Cruikshank et al., 2010 and references therein), but there are still spectral identifications that are uncertain. Clark et al. (2012) showed that a weak feature at 2.42 μm is due to trapped molecular hydrogen and is observed in dark material on multiple icy satellites. Is deuterium detectable? Clark et al., 2016 reported a possible deuterium absorption on Phoebe. Deuterium absorptions are commonly seen in OH-bearing minerals (e.g. Clark et al., 2007). A weak absorption at 2.97 μm corresponds to ammonia (Clark et al., 2008) and is seen on multiple icy satellites, but the absorption overlaps an order-sorting filter gap in the VIMS instrument where instrument errors are larger. Ammonia hydrate was also possibly detected by ground-based observers (Emery et al., 2005; Verbiscer et al., 2006). Ammonia has a strong UV absorption edge, not within the range of *Cassini* instruments, but Hendrix et al. (2010) (and independently Zastrow et al. (2012)) used *Cassini* UVIS data combined with HST data to infer the presence of a small (<1%) amount of NH_3 at Enceladus. Observations of ammonia need confirmation either by a better calibration of the VIMS data, or by further Earth-based observations. Iapetus and Hyperion have many unidentified spectral bands in the 1–5 μm region (Cruikshank et al., 2007, 2008; Clark et al., 2012; Dalton et al., 2012) that may be the signature of higher order hydrocarbons, some of which have not been measured in the laboratory. A spectral band attributed to aromatic hydrocarbons has been detected in the spectrum of Iapetus (Cruikshank et al., 2014).

Another compositional mystery that has been only partly solved is the identity of the elusive dark reddish material that acts as a chromophore in the system. For Iapetus and Phoebe Clark et al. (2012) suggest that tholins alone cannot explain the spectral features of the dark material. They showed that a combination of hydrated iron oxides and space weathered nano-metallic iron mixed with crystalline water ice explains the spectra of both Phoebe and Iapetus and that the color differences are due to abundances of the non-ice materials in the surface. The nano-phase metallic iron must be embedded in another matrix, e.g., silicates. The abundance of iron and silicates in the Saturnian system is uncertain however: The *Cassini* Cosmic Dust Analyzer (CDA) reported a dearth of iron particles in the Saturnian system (McBride et al., 2007), but other CDA data found silicate “stream” particles coming from the ring system (Kempf et al., 2005). Christon et al. (2015) found iron ions in Saturn's magnetosphere, although their abundance was only 10^{-4} that of water group ions.

For the main inner moons, the Ultraviolet Imaging Spectrograph (UVIS) (Esposito et al., 2004) on *Cassini*, which provided the first-ever opportunity to do far-UV (110–190 nm; 0.1–0.19 μm) spectroscopic investigations of icy moons in the solar system, weighed in on the identity of the reddish, low-albedo material. The Saturnian moons are known to have relatively high visible albedos (e.g. Buratti and Veverka, 1984), linked to E ring grain bombardment (e.g. Buratti et al., 2007; Verbiscer et al., 2007); however, despite their dominant water ice component, all of the icy Saturnian moons are absorbing in the ~0.2–0.5 μm region, making them dark at FUV wavelengths. For instance, Filacchione et al. (2012) used *Cassini* VIMS data to show that the spectral slope (0.35–0.55 μm) increases (becomes redder) with distance from Enceladus. Using combined UVIS, ISS, VIMS and HST data, Hendrix et al. (2018) showed that the visibly-reddish material is present on both the leading and trailing hemispheres, with increased abundances (i.e. increased absorption strength) on the trailing hemispheres and with distance from Enceladus. Filacchione et al. (2012) suggested that the source of the non-ice contaminant(s) is the main rings of Saturn, a chromophore whose reddening effects are offset by the bluing effect of E ring grains (e.g., at Enceladus). A Reddish color is also found in Saturn's rings, with the greatest degree of coloration in the C-ring; tholins have been proposed, as well as polycyclic aromatic hydrocarbons (PAH) and nanophase iron or iron oxide (Cuzzi et al., 2009). Hendrix et al. (2017) suggested that the reddish material on the satellites is related to radiolytic processing of organics within the E ring grains (Postberg et al., 2008) that make their way to the surfaces of the moons. Fig. 1 below shows an example of the presence of this chromophore, stronger on the trailing than on the leading side of Tethys.

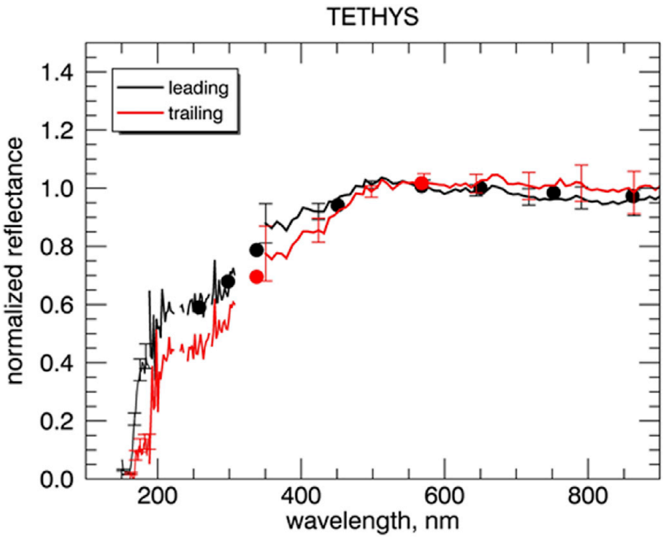

Fig. 1. Composite disk-integrated spectra from UVIS, HST, ISS and VIMS showing the red chromophore on Tethys, stronger on the trailing than on the leading side. From Hendrix et al. (2017). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

In addition to the identity of the reddish UV–visible absorber in the Saturnian system, other unanswered questions remain from the mission:

Is there a connection between the composition of the plume and the regions on Enceladus where plume deposits exist (e.g. Schenk et al., 2011)? How are the plume fallout zones compositionally different from the other zones on Enceladus that are affected by particles from the E-ring? What is the chemical make-up of the trailing side of Tethys, and why is it so reddish (Schenk et al., 2011) compared to regions dominated by the infall of E-ring grains?

3. Thermal properties

The study of thermal properties of the icy moons was not listed as a major goal of the *Cassini* mission, but it became more important after the discovery of cryovolcanism on Enceladus and the possibility of thermal segregation of frosts, particularly on Iapetus (Spencer and Denk, 2010). Prior to *Cassini*'s arrival in the Saturnian system it was known that all of Saturn's major icy satellites have albedo variations across their surfaces. At visible wavelengths Tethys, Dione and Rhea have brighter leading hemispheres (McCord et al., 1971; Morrison et al., 1976; Cruikshank, 1979; Buratti et al., 1990; Verbiscer and Veverka, 1989), while the reverse is true on Mimas and Enceladus (Buratti et al., 1990; Verbiscer and Veverka, 1992, 1994). Iapetus's albedo dichotomy is more extreme in magnitude and has a different shape: dark Cassini Regio is precisely centered at the middle of Iapetus' leading side (as first observed by Cassini in 1677). Measuring the effect this dichotomy has on the satellites' diurnal surface temperatures, to better understand their surface properties, formed an important part of the *Cassini* mission. The data