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Infrared spectroscopic characterization of the low-albedo materials on Iapetus

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ABSTRACT

Iapetus, one of the large satellites of Saturn, has been studied over the centuries for its signature brightness contrast, light on one side and dark on the opposite. It has recently been suggested that the dark material is a combination of *native* and *exogenous* materials with distinct histories. We present an analysis of parts of the Cassini Regio, the darkest region on the leading hemisphere of Iapetus, focusing on the hydrocarbon signature with a view to detect and investigate differences in the material(s). We find variations in the hydrocarbon bands with geographic location, one type predominantly located on the leading hemisphere. A comparison with the equivalent spectral features on Phoebe and Hyperion reveals a predictable resemblance between the leading hemisphere material and Phoebe and an unexpected likeness between Hyperion's darkest material and Iapetus' trailing hemisphere surface. An analysis of the slope in the visible part of the spectrum is strongly affected by a rise in the continuum (~0.35–0.65 μm) attributed to Rayleigh scattering from nano-size particles on the surface. The continuum rise varies in strength with the albedo and H_2O ice content, and when it is properly accounted for, the overall slope in all the identified spectral units is the same over the interval 0.35–2.3 μm, independent of albedo or ice abundance. The interpretation of current and previous results offers two different scenarios illustrated by the presence of one vs. two dark materials distributed over the Iapetus surface. We describe the scenarios and their implications. The appearance of the aromatic and aliphatic absorption bands together in their measured relative strengths makes this spectral signature unique, and thus enables the comparison among the three satellites.

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1. Introduction

In the more than three centuries since its discovery in 1671 by Giandomenico Cassini, Saturn's satellite Iapetus has attracted considerable attention from astronomers and planetary scientists because of its many peculiarities. First recognized for the large brightness disparity when it appears on the opposite sides of its orbit, and more recently for both the distribution of bright ice and low-albedo dust on its surface and an extraordinary equatorial ridge, Iapetus presents a number of fascinating and unique puzzles requiring investigation. Cassini's suggestion that the satellite is in locked synchronous rotation around Saturn, and that one hemisphere is essentially black and the other white, was confirmed quantitatively by ground-based telescopic observations in 1971–1974 by simultaneous measurements of the visible brightness and the heat flux (Morrison et al., 1975).

While the high-albedo (trailing) hemisphere is known to be covered with H_2O ice (Fink et al., 1976), the composition of the low-albedo material covering the leading hemisphere has remained a vexing problem. Owen et al. (2001) reviewed the composition problem in detail with telescopic data available before the *Cassini* spacecraft reached the Saturn system in 2004. In a first analysis of visible and near-infrared spectral maps of Iapetus returned by the VIMS (Visible-Infrared Mapping Spectrometer) (Brown et al., 2004), the spectral character of the low-albedo material was clearly revealed, CO_2 was discovered, and additional absorption bands were found (Buratti et al., 2005a,b; Clark et al., 2008, 2012). In terms of overall composition, Owen et al. (2001) found that a mixture of H_2O ice and Titan tholin matched the dark material spectrum over the full range 0.3–3.9 μm (ground-based telescopic observations), reinforcing the view expressed in earlier papers that a complex organic solid is responsible for the red color of the dark material. Further bolstering the role of organic solids in the spectral properties of the low-albedo material, Cruikshank et al. (2008) demonstrated the presence of both aromatic and aliphatic hydrocarbons in the VIMS spectra. However, Clark et al. (2012) found a better spectral match to the Cassini VIMS data (0.4–5.1 μm) with nano-size particles of neutral iron and FeO as the coloring agent and the material responsible for a Rayleigh component of the surface scattering that affects the shape of the spectrum shortward of about 0.7 μm.

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The nature and origin of the low-albedo material presents several challenges for observation and interpretation. It is largely confined to the leading hemisphere of Iapetus, centered on the apex of the satellite's orbital motion around Saturn, and thus appears to have been deposited from an external source. As such, it is relatively young because it has not been pierced more than a few times by small meteoroid impacts. The small number of visible impact scars indicates that the dark material is of modest thickness and that it is underlain by H_2O ice. Observations with the Cassini RADAR instrument indicate that the layer of dark material is a few tens of cm thick (Ostro et al., 2010), consistent with the general model of accretion from an external source. This implies that the mass of dark material needed to cover the leading side of Iapetus is ~three orders of magnitude smaller than previously thought (Matthews, 1992), i.e. at the most of the order of a few 10^{18} g (Tosi et al., 2010). The external source has long been thought to be Saturn's irregular and more distant satellite, Phoebe, which, on the basis of its orbital characteristics, is presumed to be a body captured after its condensation elsewhere in the Solar System (Soter, 1974; Johnson and Lunine, 2005).

The possible mechanism by which dust originating at Phoebe could be transported to Iapetus has been clarified by the discovery of a large dust ring surrounding Saturn and occupying Phoebe's orbit (Verbiscer et al., 2009). The dust ring, presumably of impact origin, is optically thin and cannot be seen at visual wavelengths, but was revealed by its infrared thermal emission, detected by the Spitzer Space Telescope. Tosi et al. (2010) find that retrograde particles of size larger than 1 μm are easily transported from Phoebe to Iapetus by means of the Poynting–Robertson mechanism, while only large prograde particles might move inward. Therefore, Tosi et al. (2010) speculate that Phoebe, while being the main dust contributor might not be the only one in the history of the system. Bottke et al. (2010) have shown that in the early epoch of Solar System history the numerous outer irregular satellites of the giant planets frequently collided, generating dust that blanketed the surfaces of the outer regular satellites. Specific to the Saturn satellites, they note that dust from both prograde and retrograde irregular satellites has coated Iapetus (and Hyperion), and that early doses of dust could have been acquired before Iapetus achieved its synchronous rotational lock. By implication, the dust on the surface of Iapetus' leading hemisphere is underlain by dust from previous episodes of deposition, and may have a different composition representative of its objects and circumstances of origin. Furthermore, the trailing hemisphere of Iapetus is likely to contain dust from earlier deposition events.

Specific to the present epoch, the dynamics of the particles spiraling inward from the current Phoebe ring have been most recently explored by Tamayo et al. (2011), who find that nearly all particles $\geqslant 10$ μm impact the leading side of Iapetus, and those that are not absorbed eventually hit Titan. Orbiting between Iapetus and Titan, Hyperion receives an optically significant coating of particles of order 5 μm in size, distributed more or less uniformly over the surface as a consequence of Hyperion's chaotic rotation. The nature of the dark material in the context of Hyperion's surface is explored in more detail by Dalton et al. (2012).

In a study of the color and distribution of the dark material on Iapetus using color imaging data from the *Cassini* Imaging Science Subsystem (ISS), Denk et al. (2010) found that the dark material that covers most of the leading hemisphere has a substantially redder color than the low-albedo material that partly intrudes on the bright, icy trailing hemisphere.

In this paper we seek in part to find any distinguishing spectral differences between the two color types identified by Denk et al. (2010) in the *Cassini* VIMS spectra by means of a systematic study of the spectral signature of the dark material across various terrains on the surface of the satellite. We then apply our technique to the analysis of the darker terrains of two other satellites, Phoebe and Hyperion, with a view to support dynamical theories of the origin and evolution of the material.

2. Data description

Our analysis is based on Cassini Visible-Infrared Mapping Spectrometer (VIMS) observations of Iapetus. The dataset consists of a selection of 30 VIMS data cubes obtained during the September, 2007 flyby. The cubes were selected because of their high spatial resolution and large spectral coverage (both visible and infrared exposures were available). We used a mosaic of the cubes that was made using the post-encounter pointing information, optimized in terms of spatial resolution and coverage by re-sampling pixels and rejecting those with low signal precision or data flaws. See Pinilla-Alonso et al. (2011) for a detailed description of the mosaic and procedure adopted to assemble it.

The mosaic consists of $\sim 10^4$ spectra covering the wavelength range 0.35–5.2 μm, and is shown in Fig. 1 as an overlay on the ISS map of Iapetus. The mosaic includes regions of high, low, and intermediate albedo along the equator, and a swath starting near the equator and extending to low southern latitudes and crossing regions of both high and low albedo. The minimum signal-to-noise-ratio (SNR) for the mosaic is ~7 for wavelengths longer than 4.4 μm. The spectral resolution is 0.0073 μm with a spatial resolution of 0.50 (nominal) or 0.166 mrad/pixel (high-resolution) in the visible part of the spectrum and 0.016 μm with a spatial resolutions of 0.50 (nominal) or 0.25 × 0.50 mrad/pixel (high-resolution) in the IR. For our study we will focus on the IR part of the spectrum longward of 3 μm where the features of the aromatic and aliphatic hydrocarbons are located.

3. Analytical approach

The main challenges when studying the aliphatic and aromatic signature of the dark material on Iapetus are:

1. The relatively low SNR in each spectrum corresponding to a spatial pixel due to the limited number of counts in the 3-μm spectral region.
2. The presence of a fairly steep slope longward of 3 μm introduced in the spectrum by OH absorption.

The best way to obviate to the first problem is to make use of as many spectra as possible in order to increase the average flux. The second problem can only be resolved by removing the slope in the least intrusive and most systematic way.

To achieve the first goal we utilize a mosaic of $\sim 10^4$ spectra. The mosaicking is a fundamental tool in providing global geographical information in a direct way. Geographical mapping provides a constraint and a reality check to spectroscopic results. In fact, we usually expect real spectroscopic features to clump geographically in regions of adjacent pixels rather than being dispersed in a random fashion.

To obtain an increase in the SNR, spectra with similar characteristics have to be averaged. We utilize a statistical clustering tool to reduce the number of spectra (and increase the SNR) to a few end-members representative of the varying composition on the surface of Iapetus. The final, unsupervised, cluster configuration is independent of the random noise, while remaining sensitive to systematic errors such as instrumental effects or pixel outliers that are automatically identified and can, after careful screening, be set aside by the investigator. This user interaction provides further refinement of the clustering results. Ultimately, the clustering technique is agnostic about the meaning of the clusters and scientific interpretation requires a posteriori evaluation of the clusters.

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