Cryogenic Reflectance Spectroscopy in Support of Planetary Missions

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Abstract

Present understanding of planetary composition is based primarily on remotely-sensed data, and in particular upon ultraviolet, visible, and infrared spectroscopy. Spectra acquired by telescopic and spacecraft instruments are compared to laboratory measurements of pure materials in order to identify surface components based on characteristic absorption features.

Cryogenic spectral measurements are necessary for the study of worlds beyond the Earth's orbit. While some materials exhibit only small spectral changes as a function of temperature (Roush and Dalton 2002), many others are strongly temperature-dependent (Dalton and Clark 1998; Grundy and Schmitt 1998). For example, hydrated salts exhibit different spectral behavior under conditions appropriate to Europa (Dalton 2000) than at terrestrial temperatures (Crowley 1991). The icy satellites of the outer solar system contain significant quantities of volatile ices (Roush 2001) which do not even exist at standard temperature and pressure (STP).

A comprehensive spectral database of ices and minerals covering a wide temperature range will have applications ranging from the study of comets and Kuiper Belt objects to outer planet satellites and the polar regions of Mars. Efforts are presently underway at NASA-Ames to develop capabilities which will contribute to such a database. As spacecraft instruments feature increasing spatial and spectral resolution, appropriate laboratory reference spectra become increasingly critical to accurate interpretation of the spacecraft data.

1. Introduction

Determination of planetary surface composition using remotely-sensed spectoscopic data relies heavily on comparison to reference spectra acquired under controlled conditions in the laboratory. Telescopic and spacecraft observations in the ultraviolet, visible, and infrared portions of the spectrum all require knowledge of the fundamental spectral properties of pure materials in order to identify surface components. However, development of spectral databases for materials relevant to low-temperature surface conditions such as the Martian polar regions, satellites of outer planets, Kuiper belt objects and comets lags significantly behind mission data analysis.

The advent of imaging spectrometers such as the Galileo Near-InfraRed Imaging Spectrometer (NIMS), Mars Global Surveyor Thermal Emission Spectrometer (MGS TES), Mars Odyssey Thermal Emission Imaging Spectrometer (THEMIS), and Cassini Visible and Near-Infrared Imaging Spectrometer (VIMS) heralds a phase of exploration wherein the distributions of surface (and atmospheric) components may be determined with relative ease once the components have been identified. The high spatial resolution achievable with these modern instruments enables scientists to study the composition of individual deposits and other features of a planet or satellite. Additional imaging spectrometers are under study for the Mars 2005 mission and prospective missions to Europa, Pluto and the Kuiper Belt. Interpretation of these data will require access to reference spectra of surface materials measured under controlled laboratory conditions.

2. Mars and the Outer Solar System

Most spectral databases for minerals contain measurements performed at standard temperature and pressure (STP), or at room temperature. This is adequate for most terrestrial remote-sensing investigations. However, many minerals exhibit temperature-dependent variations in the strength, position and shape of their absorption features (Roush and Singer 1983; Singer and Roush 1985) which become pronounced at temperatures relevant to Mars, the asteroids, and the outer solar system. At orbits beyond the Earth's, planetary surfaces contain materials which do not even exist at STP. Some, such as carbon dioxide ice, which occurs at the surface of Mars and in its polar caps, are familiar to many scientists; other more esoteric species like ammonia frosts (Dalton *et al.* 2001) or sulfur dioxide ice are rarely encountered even in the laboratory.

The surfaces of the outer planet satellites are characterized by temperatures in the 50 to 150 Kelvin range. Triton, Pluto and Charon (Grundy *et al.* 1993; Satorre *et al.* 2001) reach temperatures as low as 40 K. In this range, terrestrial gases quite literally become minerals. Volatiles such as methane, carbon monoxide, acetylene and nitrogen form ices and compounds which do not exist at STP. Of those that do, the spectra of many exhibit temperature dependencies. Ordinary hexagonal water ice is noted for its strong spectral variations in response to temperature (Grundy and Schmitt 1998). In many other ices, the extent of temperature dependence is not well constrained. Because planetary composition cannot be reliably determined without recourse to reference spectra, there is a strong need for laboratory work to characterize these materials at cryogenic temperatures relevant to solar system objects. Specifically, there is a need for *reflectance* measurements of a host of substances to enable direct comparison with spacecraft and telescopic observations.

3. Laboratory Measurements

Many materials have been considered likely candidate constituents of icy satellites. These include various compounds and polymorphs of water ice, sulfur, carbon, nitrogen and oxygen, several minerals and hydrated salt compounds, and several organics of varying degrees of complexity (Delitsky and Lane 1997, 1998; Dalton 2000; Roush 2001). Many of these are products of chemistry driven by charged-particle and ultraviolet radiation (Brucato *et al.* 1997; Gerakines *et al.* 2000; Hudson *et al.* 2001; Moore *et al.* 2001; Bernstein *et al.* 2002). A number have been detected from telescopic and spacecraft observations. While most have been studied in the laboratory, few of these measurements are directly applicable to mapping of spatial distributions on icy satellites using spacecraft observations. This is usually because most measurements are not: (1) in *reflectance*; (2) in the same *wavelength* range as the spacecraft instruments; or (3) in the *temperature* range relevant to the planetary body of interest.

Much of the work on ices to date has been concerned primarily with astrophysical ices of the interstellar medium, such as the thorough compendium of Hudgins *et al.* (1993) and other works (Gerakines *et al.* 1996, 1999; Satorre *et al.* 2001; Moore *et al.* 2001). Consequently, the measurements are usually of transmittance (cf. Bernstein *et al.* (1997)) or absorbance (cf. Ehrenfreund *et al.* (1997)); neither can be converted directly to reflectance. While these are useful for identifying frequencies of diagnostic absorption features, reflectance spectra are required to derive any sort of meaningful abundance estimates. Since the shapes, depths, strengths, and positions of diagnostic features differ between transmittance, absorbance and reflectance, published values of reflectance, or of optical constants (Hudgins *et al.* 1993), from which reflectance may be derived, are needed.

A further difficulty of applying transmission or absorption measurements to reflectance spectra of icy satellites is that the laboratory studies are typically done using thin films. This is to prevent saturation in the fundamental absorption bands. However, this also results in extremely weak or nonexistent overtone and combination bands. Reflectance spectra of planetary surfaces, which are optically thick, exhibit strong overtones and combinations, which cannot be interpreted based on the thin-film data.

Published laboratory spectra of pure materials are often acquired with a particular mission (cf. Ehrenfreund *et al.* (1997); Gerakines *et al.* (1999); and others) in mind. Thus the wavelength and temperature ranges tend to be restricted to those of the instruments and bodies of interest for that particular paper. One of the more sensible restrictions is the practice of measuring spectra only in the vicinity of an important absorption feature, as in Bernstein *et al.* (1997). However, on a planetary surface, a given surface component contributes to measured spectral reflectance throughout the spectral range, not just in the immediate vicinity of its strongest absorption frequencies. Contributions to continuum and far-wing effects must be taken into account in interpretations of spacecraft observations. Spacecraft spectrometers typically measure light in the visible to near-infrared wavelengths (.3 to 5 μm; 30,000 to 2000 cm^{-1}) where reflected solar radiance is maximized. Studies of interstellar ices are typically placed in the mid- to far-infrared where fundamental absorptions are concentrated. Since many of the published studies do not cover the wavelength ranges of planetary observations, they are of limited value in interpreting data from planetary missions.

The infrared spectra of many volatile ices (Dalton *et al.* 2001) and minerals (Roush and Singer 1983) display marked temperature dependencies over the range from 4 to 300 Kelvin. An example is the hydrated salts, which are important to studies of the Galilean satellites. These have radically different spectra at 120 Kelvin than at STP (Dalton 2000) and their absorption frequencies vary noticeably over tens of degrees Kelvin. Interstellar ices are typically studied in the range of 4 to 20 Kelvins, which is not appropriate for investigations of solar system objects. Even measurements of volatile ices at 100 Kelvin are not necessarily germane to observations of Pluto, Triton or Kuiper Belt objects at 40-50 Kelvin.

4. Conclusion

A comprehensive spectral database of ices and minerals covering a wide temperature range will have applications ranging from the study of comets and Kuiper Belt objects to outer planet satellites and the polar regions of Mars. Recent efforts at NASA Ames Research Center have led to development of a cryogenic environment chamber capable of spectral reflectance measurements from 325 to 10 Kelvin. This will contribute to the development of a published spectral database which will support investigations of the Martian polar caps, the Galilean satellites, the Saturnian satellites, and objects as far as Pluto / Charon. This will be of great utility to NASA and scientists working with the Mars 2005, Galileo, and Cassini missions, as well as projected missions to Pluto and Europa. As spacecraft instruments achieve increasing spatial and spectral resolution, such laboratory reference spectra become increasingly critical to accurate interpretation of the acquired data.

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