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Identification of spectral units on Phoebe

A. Coradini [a,*], F. Tosi [a], A.I. Gavrishin [c], F. Capaccioni [b], P. Cerroni [b], G. Filacchione [b], A. Adriani [a], R.H. Brown [d], G. Bellucci [a], V. Formisano [a], E. D'Aversa [a], J.I. Lunine [d,a], K.H. Baines [f], J.-P. Bibring [g], B.J. Buratti [f], R.N. Clark [h], D.P. Cruikshank [i], M. Combes [j], P. Drossart [j], R. Jaumann [k], Y. Langevin [g], D.L. Matson [f], T.B. McCord [l], V. Mennella [m], R.M. Nelson [f], P.D. Nicholson [n], B. Sicardy [j], C. Sotin [o], M.M. Hedman [n], G.B. Hansen [l], C.A. Hibbitts [p], M. Showalter [i], C. Griffith [d], G. Strazzulla [e]

[a] *INAF-IFSI, Istituto di Fisica dello Spazio Interplanetario, Area Ricerca Tor Vergata, Via Fosso del Cavaliere 100, I-00133 Roma, Italy*
[b] *INAF-IASF, Istituto di Astrofisica Spaziale e Fisica Cosmica, Area Ricerca Tor Vergata, Via Fosso del Cavaliere 100, I-00133 Roma, Italy*
[c] *South-Russian State Technical University, Prosveschenia 132, Novocherkassk 346428, Russia*
[d] *Lunar and Planetary Laboratory and Steward Observatory, 1629 University Boulevard, University of Arizona, Tucson, AZ 85721, USA*
[e] *INAF-OACT, Osservatorio Astrofisico di Catania, Via S. Sofia 78, I-95123 Catania, Italy*
[f] *Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, CA 91109, USA*
[g] *Institut d'Astrophysique Spatiale, Université de Paris-Sud, Bâtiment 121, F-91405 Orsay, France*
[h] *US Geological Survey, Mail Stop 964, Box 25046, Denver Federal Center, Denver, CO 80225, USA*
[i] *NASA Ames Research Center, Moffett Field, CA 94035-1000, USA*
[j] *Observatoire de Paris-Meudon, 5 place Jules Janssen, F-92190 Meudon, France*
[k] *Institute for Planetary Exploration, German Aerospace Center (DLR), Rutherfordstrasse 2, D-12489 Berlin, Germany*
[l] *Department of Earth and Space Sciences, University of Washington, 310 Condon Hall, Box 351310, Seattle, WA 98195-1310, USA*
[m] *INAF-OAC, Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, I-80131 Napoli, Italy*
[n] *Cornell University, 418 Space Sciences Building, Ithaca, NY 14853, USA*
[o] *Laboratoire de Planétologie et Géodynamique, Université de Nantes, 2 rue de la Houssinière, B.P. 92208, F-44322 Nantes Cedex 3, France*
[p] *Planetary Sciences Institute NW, 225 S. Lake Avenue, Suite 300, Pasadena, CA 91101, USA*

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Abstract

We apply a multivariate statistical method to the Phoebe spectra collected by the VIMS experiment onboard the Cassini spacecraft during the flyby of June 2004. The G-mode clustering method, which permits identification of the most important features in a spectrum, is used on a small subset of data, characterized by medium and high spatial resolution, to perform a raw spectral classification of the surface of Phoebe. The combination of statistics and comparative analysis of the different areas using both the VIMS and ISS data is explored in order to highlight possible correlations with the surface geology. In general, the results by Clark et al. [Clark, R.N., Brown, R.H., Jaumann, R., Cruikshank, D.P., Nelson, R.M., Buratti, B.J., McCord, T.B., Lunine, J., Hoefen, T., Curchin, J.M., Hansen, G., Hibbitts, K., Matz, K.-D., Baines, K.H., Bellucci, G., Bibring, J.-P., Capaccioni, F., Cerroni, P., Coradini, A., Formisano, V., Langevin, Y., Matson, D.L., Mennella, V., Nicholson, P.D., Sicardy, B., Sotin, C., 2005. Nature 435, 66–69] are confirmed; but we also identify new signatures not reported before, such as the aliphatic CH stretch at 3.53 µm and the ∼4.4 µm feature possibly related to cyanide compounds. On the basis of the band strengths computed for several absorption features and for the homogeneous spectral types isolated by the G-mode, a strong correlation of CO_2 and aromatic hydrocarbons with exposed water ice, where the uniform layer covering Phoebe has been removed, is established. On the other hand, an anti-correlation of cyanide compounds with CO_2 is suggested at a medium resolution scale.

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[*] Corresponding author. Fax: +39 06 4993 4182.
E-mail address: coradini@ifsi-roma.inaf.it (A. Coradini).

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1. Introduction

Phoebe, ninth satellite of Saturn (S IX), was discovered by W.H. Pickering in 1898. Phoebe has several peculiar properties. Its retrograde orbit, with large semi major axis (12.952 million km or 214.9 Saturn radii, >10 times the one of Titan), coupled with its relatively high eccentricity ($e = 0.1644$) and high inclination ($i = 174.75°$), suggests that this moon had not formed in the Saturn environment, but is an external body permanently trapped by Saturn's gravity (Pollack et al., 1979). From this point of view, Phoebe resembles the outermost satellites of Jupiter, Uranus and Neptune, which are "irregular" as well.

Images taken from the Voyager 2 spacecraft on 4 September 1981, despite the great distance of the flyby (2.076 million km), had first shown that Phoebe is a roughly spherical and dark object with a diameter of about 210 km and a mean albedo of 0.07, with some isolated, quasi-circular bright spots at high northern and southern latitudes, which exhibit albedos up to 0.11, i.e., ~50% greater than the rest of the dark, bland areas (Thomas et al., 1983). Unfortunately, the low resolution Voyager images did not permit inferring the origin of these bright markings; nonetheless, from these and other spectrophotometric data, Phoebe was initially related to C-type and D-type asteroids, like the "Trojan" asteroids moving on Jupiter's orbit or the "Centaurs" orbiting between Jupiter and Neptune (Cruikshank et al., 1983, 1984). Phoebe's dimensions and its asynchronous rotational period (9.2735 ± 0.0006 h; Bauer et al., 2004) are also similar to those measured for many asteroids. Furthermore, Phoebe was invoked to be the source of the dark material coating the leading hemisphere of Iapetus: according to the first version of the exogenous model (Soter, 1974), particles from Phoebe spiraled towards Saturn in retrograde orbits due to the Poynting–Robertson effect, and collided with Iapetus' leading side.

On 11 June 2004, the real nature of this satellite was uncovered during the flyby of Cassini–Huygens. Some 19 days before the spacecraft entered orbit around Saturn, it reached the closest approach of 2068 km from Phoebe, i.e., ~1000 times closer than the Voyager 2, at 19:33 SCET (*spacecraft event time* or UTC onboard the spacecraft), with a relative velocity of 6.35 $\mathrm{km\,s^{-1}}$. The average diameter of Phoebe was determined to be about 213 km, whereas its mass was inferred from precise tracking of the spacecraft and optical navigation. The measurements yielded a value of $\mathrm{GM} = 0.5527 \pm 0.001\ \mathrm{km^3\,s^{-2}}$ (Jacobson et al., 2004); this, combined with an accurate volume estimate from the images, led to a calculated mean density of about $1630 \pm 33\ \mathrm{kg\,m^{-3}}$ (Jacobson et al., 2004), much lighter than most rocks, but heavier than pure water ice at approximately $930\ \mathrm{kg\,m^{-3}}$. This value is higher than the mass-averaged density of the regular satellites of Saturn, again supporting the evidence that Phoebe is a captured body (Johnson and Lunine, 2005).

From the images acquired by the Cassini multispectral camera, Phoebe appeared to be an irregularly shaped body, with overlapping craters of varying sizes. This morphology suggests an old surface. The many craters smaller than 1 km indicate that projectiles smaller than 100 m once bombarded Phoebe. All of the images show evidence for an ice-rich body mantled with a layer of dusty dark material, whose thickness can change from area to area (see Fig. 1). Further evidence for this can be seen on some crater walls where the darker material appears to have slid downwards, exposing more light-colored material.

The first spectral analysis performed on the VIMS data (Clark et al., 2005) pointed out the existence of ferrous iron-bearing minerals, bound water, carbon dioxide, probable phyllosilicates, organics and cyanide compounds. This mix of surface materials has not been encountered elsewhere: the emerging view of Phoebe is that it might have been part of an ancestral population of icy, comet-like bodies, some of which now reside in the Kuiper belt beyond Neptune.

The quality of Cassini data enables more detailed analyses on selected areas of the satellite. The application of the G-mode method to the infrared spectra of Phoebe acquired by VIMS—essentially an automatic classification of its surface—allows us to identify some spectral features correlated with location or geology on the satellite; moreover, this is also a test of the reliability of the method, to be used in the future on other VIMS observations of Saturn's icy moons.

2. The VIMS instrument

The *Visual and Infrared Mapping Spectrometer* (VIMS) is an imaging spectrometer onboard the Cassini Orbiter spacecraft. VIMS is actually made up of two spectrometers, VIMS-V (developed in Italy) and VIMS-IR (developed in the USA). VIMS is the result of an international collaboration involving the space agencies of the United States, Italy, France and Germany (Miller et al., 1996) as well as other academic and industrial partners.

The two channels share a common electronics box and are co-aligned on a common optical pallet. The combined optical system generates 352 two-dimensional images (with maximum nominal dimensions of 64 × 64, 0.5 mrad pixels), each one corresponding to a specific spectral channel. These images are merged by the main electronics in order to produce "image cubes" representing the spectrum of the same field of view (FOV) in the range from 0.35 to 5.1 μm, sampled in 352 bands. See Brown et al. (2004) for a complete description of the instrument (Table 1).

In the following, we considered only the IR portion of VIMS spectra, i.e., the data acquired by VIMS-IR. Infrared data are generally more diagnostic for the composition of solid surfaces; however, in principle, the classification operated by the G-mode can be performed on the basis of all of the available bands, especially when both VIMS-V and VIMS-IR operate in nominal