letters to nature

Compositional maps of Saturn's moon Phoebe from imaging spectroscopy

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The origin of Phoebe, which is the outermost large satellite of Saturn, is of particular interest because its inclined, retrograde orbit suggests that it was gravitationally captured by Saturn, having accreted outside the region of the solar nebula in which Saturn formed[1]. By contrast, Saturn's regular satellites (with prograde, low-inclination, circular orbits) probably accreted within the sub-nebula in which Saturn itself formed[2]. Here we report imaging spectroscopy of Phoebe resulting from the Cassini–Huygens spacecraft encounter on 11 June 2004. We mapped ferrous-iron-bearing minerals, bound water, trapped CO_2, probable phyllosilicates, organics, nitriles and cyanide compounds. Detection of these compounds on Phoebe makes it one of the most compositionally diverse objects yet observed in our Solar System. It is likely that Phoebe's surface contains primitive materials from the outer Solar System, indicating a surface of cometary origin.

We report the identification and possible origins of the surface materials on Phoebe by compositional mapping with the Visible and Infrared Mapping Spectrometer[3] (VIMS) on board Cassini. Cassini VIMS spatially resolved the surface of Phoebe, and data have been registered and projected into simple cylindrical maps: low to medium resolution with near hemispheric coverage, and high resolution of a small area (Fig. 1). Spectra of Phoebe indicate a low albedo surface, from <1% to 6% reflectance (Fig. 2), with a variety of absorption features. These features are due to materials (Table 1) that occur with variable abundances and/or grain sizes in different locations on the body. They include: previously identified water ice[4], bound water, and trapped CO_2 (maps, Fig. 1; spectra, Fig. 2). A broad 1-µm feature, attributed to Fe^{2+}-bearing minerals, is present in almost all regions but stronger in equatorial areas. Bound water and hydroxyl absorptions indicate the presence of phyllosilicates. Other weak spectral

features may be caused by cyanide and organic compounds.

The composition of Phoebe should reflect the composition of the region in the solar nebula where it accreted. If Phoebe originated in the region of the asteroid main belt (~3 AU), it should consist largely of volatile-poor mafic minerals. Alternatively, it could have accreted in the volatile-rich outer solar nebula where the Kuiper belt objects (KBOs) originated. Dynamical scattering inward from an accretion site among the KBOs is more likely than scattering outward from the asteroid belt[5]. For example, inward scattering may have occurred during events that are thought to have forced the KBOs outward by the outward migration of Neptune[6].

With a diameter of 220 km, Phoebe is comparable in size to most of the nearly 800 known KBOs. Other physical properties that Phoebe shares with KBOs include the presence of H_2O ice and an overall low surface albedo[7]. KBOs exhibit a wide range of colour[8], including the neutral colour characteristic of Phoebe[9]. It has been postulated that material from Phoebe (for example, ejected by impacts) may coat the leading surface of Saturn's moon Iapetus[10], so this material might be found elsewhere in the Saturn system.

Mapping results from VIMS indicate that H_2O ice is distributed over most of Phoebe's observed surface, but generally shows stronger spectral signatures toward the southern polar region (Fig. 1b, h). In the highest spatial resolution data, crater interiors display less exposed ice than the surrounding terrain (arrows in Fig. 1b). In the jovian system, cratering tends to expose fresh ice in the subsurface[11]. The highest resolution VIMS data for Phoebe also indicate an ice-rich layer exposed in crater walls just below Phoebe's surface (Fig. 1b). Therefore, it is likely that ice is less abundant in the deeper subsurface, at least in the region of highest resolution data (near longitude 0°, latitude 0°).

The Fe^{2+} absorption is quite broad (Fig. 2b, feature f1), unlike that in pyroxenes, but similar to that in olivines and phyllosilicates[12]. If phyllosilicates were present, $(OH)^-$ absorptions might be expected, but would be relatively weak owing to the low reflectance. Indeed, weak 2.2- and 2.3-µm absorptions (f10, f23) are

Table 1 **Observed spectral features**

Feature	Wavelength (µm)	Width (µm)	Origin
f1	1.0	1.1	Probable Fe^{2+}
f2	1.04	~0.05	H_2O ice overtone
f3	1.2	~0.02	OH stretch, CH combination, or calibration artefact
f4	1.3	~0.02	OH stretch, CH combination, or calibration artefact
f5	1.4	~0.02	OH stretch, CH combination, or calibration artefact
f6	1.5	~0.2	H_2O ice overtone
f7	1.7	Variable	CH stretch overtone
f8	1.95	~0.1	Bound H_2O
f9	2.02	~0.2	H_2O ice combination
f10	2.16	~0.03	Probable metal-OH combination, for example, phyllosilicates
f11	2.42	~0.07	Probable CN combination
f12	2.95	~0.7	H_2O ice and/or bound H_2O
f13	3.1	~0.05	H_2O ice Fresnel peak
f14	3.2–3.3	Variable	CH stretch fundamentals
f15	3.55	~0.06	Probable CH
f16	3.9	~0.2	Perhaps CH, CN or H_2O
f17	4.26	~0.03	Trapped CO_2 (gaseous or fluid inclusion)
f18	4.50	~0.03	CN in a nitrile
f19	4.8–5.0	~0.05	Probable CN fundamental
f20	>5.1	ND	ND
f21	4.3	0.7	H_2O ice and/or bound water
f22	2.05	~0.17	H_2O ice
f23	2.3	~0.08	Probable metal-OH combination, for example, phyllosilicates
f24	2.72	~0.05	OH stretch fundamental, common in phyllosilicates
f25	1.25	~0.1	H_2O ice
f26	3.62	~0.07	Probable CH or CN
f27	2.54	~0.016	Probable CH

ND, not determined.

seen in some spectra, indicating a probable metal-OH absorption (Fig. 2b). Hydrated mineral absorptions are also consistent with phyllosilicates. We attribute the 1.5- and 1.95-μm absorptions (Fig. 2b, spectrum S2, f6, f8) to hydrated mineral absorptions, but these features are not diagnostic of specific mineralogy and indicate only the presence of bound water.

CO_2 is ubiquitous on Phoebe. The wavelength and shape of the CO_2 absorption, 4.26 μm (Fig. 2a, c, d, f17), is similar to that of the trapped CO_2 found on Jupiter's satellites Callisto and Ganymede[11]. CO_2 is more spatially variable than water ice in the areas where it maps on Phoebe's surface (Fig. 1g). The highest spatial resolution data indicate a linear structure of lower CO_2 that is at least 60 km in length (Fig. 1g). Medium resolution data indicate other linear

structures of variable CO_2 abundances, showing structures only seen in composition maps (Fig. 1g) and not observed in reflectance (Fig. 1a).

The absorption feature at 2.42 μm (Fig. 2a, c, e, f11) has not been reported on any Solar System body before Cassini. Searches of available spectral libraries[12,13] and scientific papers that show OH-bearing minerals with an absorption at this position also have other absorptions nearby that are not seen in Phoebe spectra. Cyanide compounds, however, have unique absorptions in this region, and a spectrum of potassium ferrocyanide trihydrate, $K_4Fe(CN)_6 \cdot 3H_2O$, closely matches Phoebe's absorption position and shape (Fig. 2e). Spatially, the 2.42-μm absorption maps mainly in the equatorial regions (Fig. 1e). The same 2.42-μm absorption has been observed
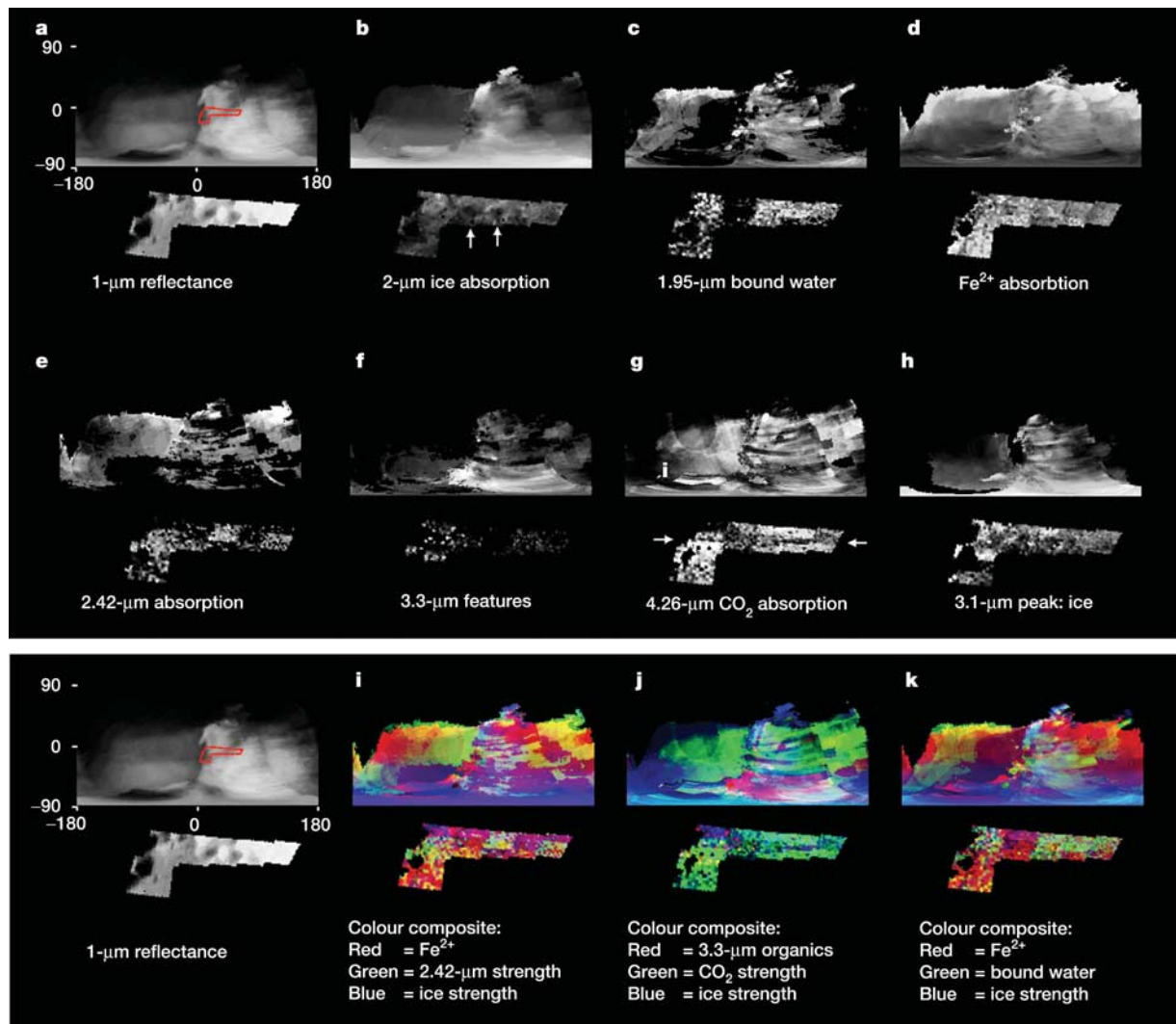

Figure 1 VIMS data, x and y axes show longitude and latitude, respectively, in degrees. **a**–**h**, Compositional maps of Phoebe in simple cylindrical projection, VIMS obtained spatially resolved hyperspectral images of Phoebe at 352 wavelengths (0.4–5 μm) from 8:47 UT June 11, 2004 at an initial range of 245,833 km and phase angle of 84.9°, to 10:22 UT June 12, 2004 at a final range of 338,401 km and phase angle of 92.2°. The closest image was obtained on 19:32 UT June 11 at a range of 2,178 km and solar phase angle of 24.6°. For each map, two resolutions are shown: medium resolution (top) sampled at 0.5° per pixel (about 1.9 km at the equator), and high resolution sampled at 0.48 km pixel^{-1} (original VIMS resolution was 0.96 km pixel^{-1}). The spatial mapping of the VIMS, with an instantaneous field of view of 0.25 × 0.5 mrad, resulted in spatial coverage at full spectral resolution (~0.016 μm) up to 1 km per pixel, allowing many diagnostic absorption features to be mapped. **a**, The apparent reflectance at 1 μm is shown, ignoring lighting due to slope variations. The red outline shows the region of the

high resolution image. **b**–**h**, The continuum-removed absorption band depth is shown for each material, as defined in ref. 21. **b**, The 2-μm ice absorption strength. Note that two craters (arrows) have no ice in the floors. The crater on the right shows enhanced ice strength near the top of the crater (bright arc). Other materials map in the floors of the two craters, for example, Fe^{2+}-minerals (**c**). Maps of probable cyanide compounds (**e**), probable organics (**f**), CO_2 (**g**), and high abundance crystalline water ice (**h**) are shown. A curious linear structure seen in the map of CO_2 is indicated by the two arrows in **g**. That structure is not seen in other compositional maps, nor in reflectance (**a**). **i**–**k**, Colour composite mineral maps showing complex spatial relationships of materials across Phoebe's surface, compared to the reflectance image (**a**; shown again as the black and white image on left). **i**, Fe^{2+}-bearing minerals, probable cyanide compounds, and water ice. **j**, Organic materials, CO_2, and water ice. **k**, Fe^{2+}-bearing minerals, bound water and water ice.

in the first VIMS data of the dark side of Iapetus[14]. A similar absorption was also seen in comet Borrelly[15].

Certain regions of Phoebe exhibit weak absorptions in the 3.3-μm region (Figs 1f and 2d, f14), indicating the presence of organics. Both the position of the CH stretch fundamental near 3.3 μm, and the lack of absorptions in the 3.4–3.7 μm region[16], argue for an aromatic or cycloalkane hydrocarbon origin and against long chain

aliphatics. The lack of spectral structure observed in the VIMS spectral range for pyrene and anthracene rejects these aromatics.

Other areas of Phoebe show absorption features at 4.50 and 2.54 μm (f18 and f27), as well as in the 3.3-μm region (Figs 1f and 2a, d). The narrow 4.5-μm absorption indicates a CN triple bond (C≡N). The best solution for these spectra appears to be an alkane molecule (single bonded CC) with an attached CN, a nitrile group.
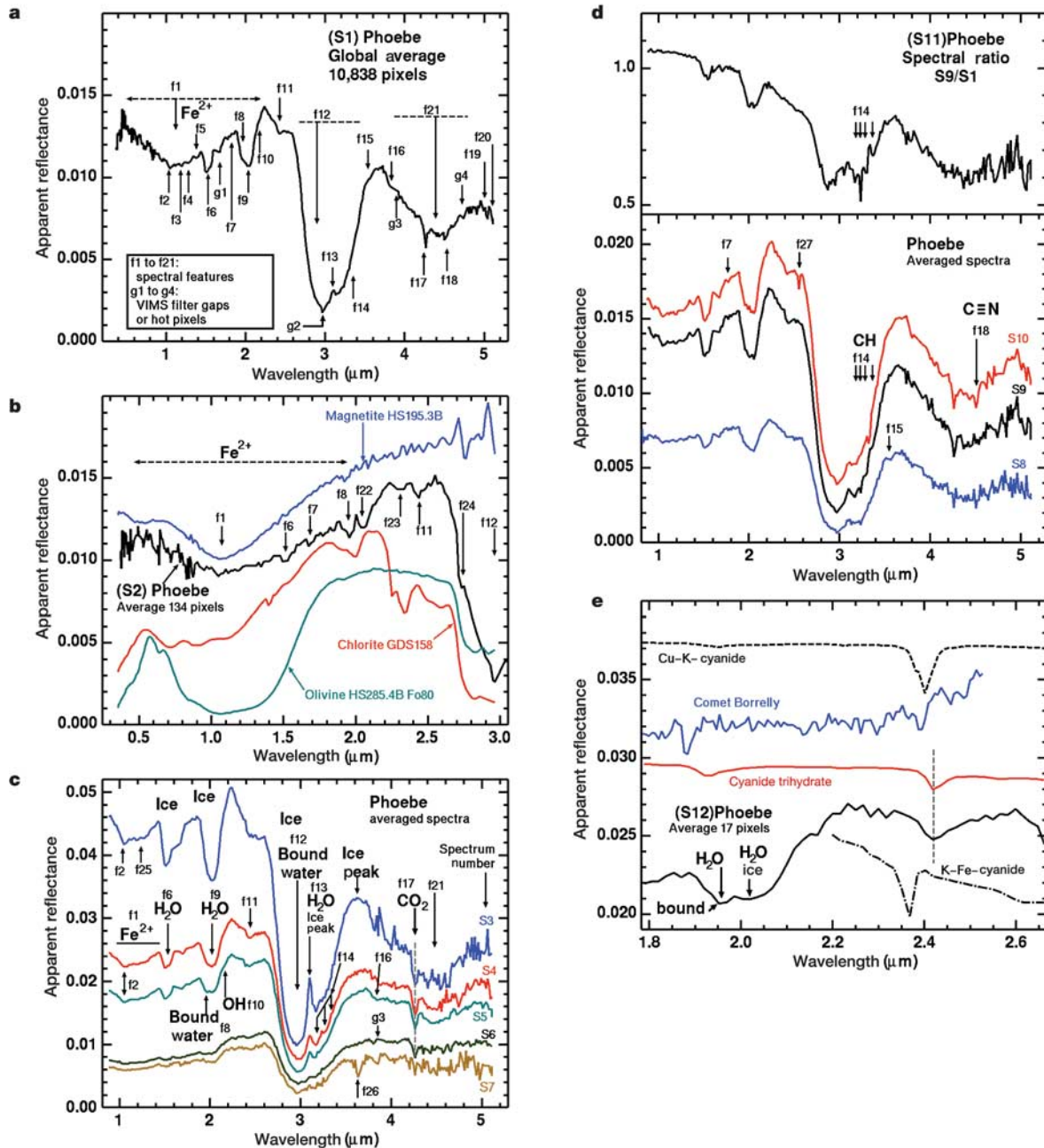

Figure 2 Spectra of Phoebe show the presence of numerous compounds. Spectra are labelled S1–S12, and spectral features are labelled f1–f27. VIMS grating filter gaps are labelled g1–g4, and should be ignored. **a**, An average of over 10,000 VIMS pixels shows the highest signal-to-noise ratio spectrum, covering most of the images shown here (avoiding high emission angle pixels near the edge of the map). The CO_2 absorption (f17) occurs at a wavelength shorter than that observed in spectra of solid CO_2. Other spectra (**b**–**e**) are averages from the brightest pixels in Fig. 1, excluding high emission angle pixels near the edge of the map. **b**, Phoebe spectra compared to three of many Fe^{2+}-bearing minerals[12] with similar absorptions. **c**, Illustration of the spectral diversity of Phoebe's surface. These spectra are averages from multiple small locations on Phoebe's surface, obtained from unprojected data. **d**, Phoebe spectra showing organic and nitrile

absorptions. **e**, Comparison of Phoebe spectra to cyanide compounds[12] and to spectra of comet Borrelly[15]. Cyanide compounds have a CN fundamental stretch in the 4.7–5-μm region, and the position of the fundamental as well as the 2.4-μm absorption varies with the compound's specific composition[12]. Although the VIMS' signal-to-noise ratio in that spectral region is low, areas on Phoebe with the strongest 2.42-μm absorption show spectral structure similar to that expected from a cyanide origin. Because the CN fundamental would show saturated spectral structure, the observed spectral structure would be weak. The broad 3.9- and 4.5-μm features (**a**, **c**, f16, f21) may be organic related, or due to spectral structures in the Fe-bearing minerals, bound water-bearing minerals, water ice, or other materials not directly observed in the spectra.

Our studies indicate that organic materials with a few per cent nitrile approximately match the Phoebe spectra. A spectral feature at 3.62 μm is seen in some Phoebe spectra (Fig. 2c, f26, Table 1). This absorption is not accompanied by other nearby features that might indicate an organic origin. A spectrum of HCN (ref. 16) shows a similar isolated absorption.

The low albedo of Phoebe is probably caused by carbon and/or organic molecules. Some asteroids with low albedo have been associated with certain meteorite classes that are rich in organic materials[17,18]. Unfortunately, the lower spectral resolution of the asteroid data prohibits direct comparison to the VIMS Phoebe spectra.

Spectra of Phoebe display a wealth of information, indicating a surface containing distinct locations of ferrous-iron-bearing minerals (Fig. 1d), bound water (Fig. 1c), trapped CO_2 (Fig. 1g), probable phyllosilicates, organics (Fig. 1f), nitriles and cyanide compounds (Fig. 1e). The only body imaged to date that is more compositionally diverse is Earth. Phoebe's organic and cyanide compositions are unlike any surface yet observed in the inner Solar System. Although this composition is more similar to comets, the water ice may only be a surface coating because some crater interiors show less water ice deep in the crater and more water near the surface (Fig. 1b). This raises the possibility that Phoebe is coated by material of cometary or outer Solar System origin. Without information about its deep internal composition, it is not possible to conclude that Phoebe has an outer Solar System origin. Nevertheless, compositional data for the full Saturn system may help constrain Phoebe's origin. The same broad Fe^{2+} absorption on Phoebe is seen in Saturn's rings, particularly in the Cassini division and the C-ring[19], and may imply that some materials are common to both Phoebe's surface and the rings. But organics and cyanide compounds have yet to be definitively detected in any VIMS Saturn ring data to date, despite much higher signal-to-noise ratios than obtained on Phoebe. This may mean that the materials on Phoebe and the rings have different origins.

The low albedo and neutral colour (at visible wavelengths) of Phoebe are probably caused by the presence of carbon, iron-bearing minerals, and some quantity of complex organic compounds. Organic molecules tend to impart red coloration to a planetary surface, although a moderate degree of colour can also come from mafic minerals such as Mg-rich pyroxene[20]. The neutral reflectance of Phoebe suggests that amorphous or moderately structured elemental carbon dominates the colour, and that the effects of the minerals and organic complexes are minimal. The detection of compounds with a 2.42-μm absorption on both Phoebe and Iapetus may indicate that material from Phoebe has struck Iapetus's leading hemisphere. Alternatively, perhaps cometary material has coated both Phoebe and Iapetus. Regardless of its origin, Phoebe's diverse mix of surface materials is unique among Solar System surfaces observed to date, and it probably samples primitive materials in the outer Solar System.   □

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Saturn's moon Phoebe as a captured body from the outer Solar System

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The orbital properties of Phoebe, one of Saturn's irregular moons, suggest that it was captured by the ringed planet's gravitational field rather than formed in situ. Phoebe's generally dark surface shows evidence of water ice[1], but otherwise the surface most closely resembles that of C-type asteroids[2] and small outer Solar System bodies such as Chiron and Pholus that are thought to have originated in the Kuiper belt[3]. A close fly-by of Phoebe by the Cassini–Huygens spacecraft on 11 June 2004 (19 days before the spacecraft entered orbit around Saturn) provided an opportunity to test the hypothesis that this moon did not form in situ during Saturn's formation, but is instead a product of the larger protoplanetary disk or 'solar nebula'. Here we derive the rock-to-ice ratio of Phoebe using its density[4,5] combined with newly measured oxygen and carbon abundances in the solar photosphere[6,7]. Phoebe's composition is close to that derived for other solar nebula bodies such as Triton and Pluto, but is very different from that of the regular satellites of Saturn, supporting Phoebe's origin as a captured body from the outer Solar System.

One characteristic that might help determine whether Phoebe originated in the solar nebula or the 'circum-saturnian' disk is the ratio of water ice to other materials in its interior, inferred from the average density of the object. The mean density of the 'regular' satellite system of Saturn is $1,300\,kg\,m^{-3}$, with an uncertainty of approximately ±10% (ref. 8). This is the mass-weighted value for Mimas, Enceladus, Tethys, Dione, Rhea and Iapetus—moons with prograde, in-plane, essentially circular orbits well inward of