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

Phoebe's retrograde and eccentric orbit. The uncertainty is based on those reported for the individual satellite densities, weighted by their mass. We excluded irregular Hyperion because it may be a remnant of a larger object disrupted by collision. This moon's mass is so small that its exclusion does not alter the system's mean density to the level of accuracy we give here. We also excluded Titan. Its density, corrected for the strong effects of compression of the ice caused by its large mass, is $1,600 \, \text{kg m}^{-3}$, but Titan is massive enough that loss of water during formation might have altered significantly its overall ratio of rock to ice. Phoebe's density, based on the mass determined by measuring the perturbation of the spacecraft's trajectory associated with the Phoebe fly-by and the volume determined by analysis of imaging science subsystem data, is $1,630 \pm 33 \, \text{kg m}^{-3}$ (refs 4, 5).

Phoebe's mass is too small to compress water ice or silicate significantly, so the derived density for Phoebe is equal to that of the material in the absence of pressure effects. Likewise, the central pressure of Phoebe (~4 MPa) is more than an order of magnitude less than that required for high-pressure phases of water ice to be stable. However, the low pressures in the interior of this body also allow for significant void space, or porosity, to be maintained. Porosities of small Solar System bodies are poorly constrained, but have been estimated for various small asteroids and satellites as being between 0.2 and 0.6 (ref. 9). Figure 1 shows the range of Phoebe's equivalent 'sample density' (without porosity) for various assumptions for porosity. If Phoebe's porosity were 0.5, it could be made entirely of anhydrous silicates. However, Cassini's Visible and Infrared Mapping Spectrometer (VIMS) detected abundant water ice and water bound to minerals[10], making a purely silicate composition unlikely. We therefore take the plausible range of porosity of Phoebe to be from near zero to about 50%.

The uncompressed densities of Pluto, a Kuiper belt object, and Neptune's satellite Triton, which may have originated in the Kuiper belt before being captured by Neptune, are both around $1,900 \, \text{kg m}^{-3}$ (refs 11, 12). If Phoebe were derived from the same compositional reservoir as Pluto and Triton, its present porosity would have to be ~0.15 to attain the same material density. Even
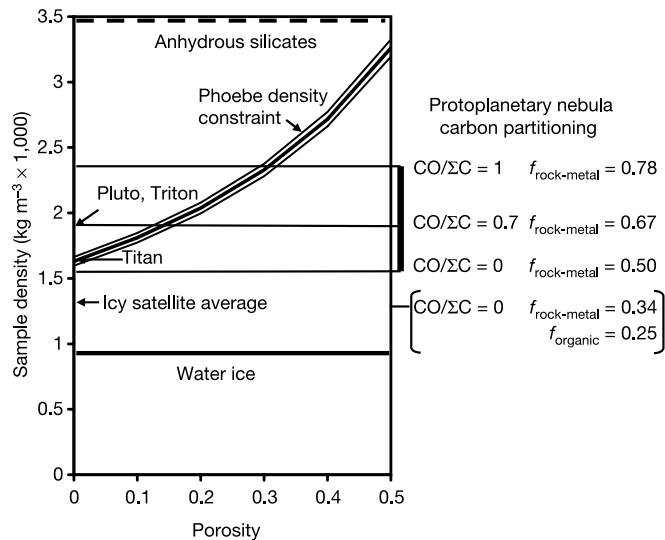
if the porosity of Phoebe were zero, its Cassini-derived density would be 1σ above that of the regular icy saturnian satellites. Therefore, Phoebe appears to be compositionally different from the intermediate-sized regular satellites of Saturn.

To quantify the compositional differences, we calculated the mass fractions of rock and ice in Phoebe, constrained by its observed density and the range of plausible porosities. For a protoplanetary disk of cosmic composition the dominant solid-forming element is oxygen (O), which will combine with silicon and magnesium to form magnesium silicates (calcium-aluminium silicates are less abundant because of the smaller cosmic abundances of Al and Ca compared with Mg), with iron to form various oxides, and with hydrogen to form water[13]. We adjusted the rock-to-ice ratio by taking solar abundances of magnesium, silicon and oxygen and forming $MgSiO_3$ (enstatite) as the 'rock' phase, which is seen in chondrites. We assume that sulphur takes up iron, but as the latter is more abundant we allow FeO to form until the iron is depleted, and add nickel to this 'metal' phase. The nickel abundance is sufficiently small to have little bearing on the density. The oxygen remaining is partitioned into water and carbon-bearing molecules, mostly carbon monoxide.

The abundance of CO that was in the protoplanetary or circum-saturnian disk is poorly constrained; a very reducing disk would have essentially all the carbon in methane (CH_4) and other organic phases. Carbon dioxide is not important as a sink for oxygen in any protoplanetary or circum-saturnian disk model[13]. We set $CO/(CO + CH_4)$ to be a free parameter and examined the consequences of allowing this to range from 0 to 1. We then computed the mass fractions of rock (f_{rock}), metal (f_{metal}) and water ice (f_{ice}) via[14]:

$$\rho_{Phoebe} = [(f_{rock}/\rho_{rock}) + (f_{metal}/\rho_{metal}) + (f_{ice}/\rho_{ice})]^{-1}$$

We adopted standard densities for the silicate ($3,360 \, \text{kg m}^{-3}$), which was assumed to be anhydrous and is consistent with the density of the almost-certainly dehydrated moon Io, the metallic sulphide/oxide phase ($4,800 \, \text{kg m}^{-3}$), and water ice ($940 \, \text{kg m}^{-3}$)[15]. The hydration state of the silicates in the protoplanetary disk, or circum-saturnian disk, is poorly constrained. Most cosmochemists argue that hydration was limited in the former[16], but Jupiter's moon Europa has an ice layer whose mass is consistent with dehydration of the moon's silicate bulk[17]. However, if we choose hydrated silicates in our model—and hence a lower density for the silicate phase—the amount of water declines commensurately. Therefore, there is little difference in making one choice or the other, and for concreteness we consider anhydrous silicates only.

Because the carbon abundance is approximately half that of oxygen in a solar composition gas, the precise abundances of these two elements are crucial in quantifying the rock mass fraction in Phoebe and the other saturnian satellites. Recent reanalysis of solar photospheric abundances[6,7] have revised the oxygen abundance, and to a much lesser extent the carbon abundance, downward relative to the previously accepted values[18]. Expressed in the standard way, with the logarithmic (base 10) abundance of hydrogen set to 12.00, oxygen is 8.66 and carbon is 8.39. For these values, and currently accepted silicate/metal abundances[18], we find the rock and metal mass fraction $f_{rock-metal} = 0.785$ and $\rho_{Phoebe} = 2,310 \, \text{kg m}^{-3}$ when CO is the sole carbon-bearing molecule. When CH_4 is the only carbon-bearing molecule, $f_{rock-metal} = 0.505$ and $\rho_{Phoebe} = 1,520 \, \text{kg m}^{-3}$. The upper density is consistent with Phoebe's measured density if the satellite has a porosity of ~0.3. The lower density is not consistent with the measured density. However, allowing CO to be 25% of the carbon budget (with CH_4 the rest) yields a density of $1,620 \, \text{kg m}^{-3}$ (and $f_{rock-metal} = 0.555$), consistent with Phoebe's density for a porosity of zero.

Thus, as shown in Fig. 1, the density of Phoebe can be reproduced with the latest solar abundances of the elements and reasonable

Figure 1 Plot of the material or 'sample' density versus porosity of Phoebe using data from the Cassini orbiter. The heavy line is the central reported value, $1,630 \, \text{kg m}^{-3}$, with lighter lines on either side representing the uncertainty of $\pm 33 \, \text{kg m}^{-3}$. Densities of uncompressed water ice and anhydrous silicates are shown for comparison. Also labelled are the densities of Pluto and Triton, the mass-weighted mean density for the 'regular' icy saturnian satellites, and the density of Titan. The calculated sample densities discussed in the text are shown for different ratios of carbon contained in CO to total carbon: $CO/\Sigma C = CO/(CO + CH_4)$.

porosities for a wide range of ratios of CO (oxidized carbon) to CH_4 (reduced carbon). The upper (CO-dominated) density is of particular interest because it is close to but above the density of Pluto and Triton. A material density for Phoebe of $1,900\,kg\,m^{-3}$, the uncompressed value for Pluto and Triton given in Fig. 1, requires CO to have been 70% rather than 100% of the total carbon budget where Phoebe formed. This is still consistent with the general view that CO dominated over CH_4 in the protoplanetary disk[19], yet is also consistent with the observation of methane on Pluto and Triton[20]. The corresponding porosity for Phoebe is then 15%. So a reasonable set of numbers gives Phoebe a composition identical to that of the only Kuiper belt objects for which we possess densities.

The new elemental abundances have been challenged as an artefact of partial gravitational settling in the Sun, where the abundances are measured, such that the true primordial abundances of O and C should be raised by 0.07 dex (ref. 21). Were we to adopt the resulting O and C values, a Phoebe with zero porosity would be reproduced in a nebular model with CO as 50% of the carbon budget, rather than 25%. For a porous Phoebe, a material density of $1,900\,kg\,m^{-3}$ (identical to that of Pluto and Triton) is reproduced, with CO representing 85% of the nebular carbon budget. Neither of these scenarios represents a qualitative change from the discussion given above. In contrast, the old elemental abundances[18] cannot reproduce the high densities of Phoebe, Pluto or Triton, even if CO represents 100% of the carbon budget in the solar nebula.

With the new (or modified new) C and O abundances, it is more difficult to explain the significantly lower densities of the regular saturnian satellites, which are all assumed to have zero porosity because of their much larger masses compared with Phoebe (although outer layers with low porosity have been suggested for some of the smallest[22]). The mass-averaged value of $1,300\,kg\,m^{-3}$ cannot be reproduced even if the carbon budget includes only CH_4 and no CO. It is worth noting that this was not as much of an issue with the old solar abundances[18] used in studies before the recent revisions[6,7], as the CH_4-dominated case resulted in a model density close to $1,300\,kg\,m^{-3}$. It is possible that the formation of Saturn somehow led to a more oxygen-rich or water-rich circum-saturnian disk relative to the protoplanetary disk[23].

Alternatively, the mean density can be reduced by retaining the solar elemental oxygen abundance but postulating a phase of condensed, refractory carbon present in the interiors of these satellites. This phase would bring carbon into the satellites as its own solid phase (in contrast to the volatile CO and CH_4, which would have had to be trapped in water ice, and would not have significantly changed the satellite bulk density), and hence lower the mass fraction of high-density rock and ice. Such refractory organics are plausible, but their identity is not constrained. Data from Cassini VIMS indicate the presence of hydrocarbon-type organics in the spectrum of Phoebe itself. If they were present in significant abundance, we would calculate a lower material density of Phoebe for any given choice of porosity. For example, if 25% (by mass) of the carbon in the circum-saturnian disk were in the form of a refractory hydrocarbon with a mean molecular weight of 100 and density of $1,000\,kg\,m^{-3}$, the observed mean density of the regular saturnian satellites would be lowered to $1,300\,kg\,m^{-3}$ relative to the value obtained if all the carbon were in the form of methane. Such a hydrocarbon could consist of polymers of acetylene, a common product of methane chemistry in the absence of liquid water. If the environment in which Phoebe formed had 5% of the carbon in the form of this hydrocarbon—with the rest being CO—then the predicted density of the moon for zero porosity would fall from $2,310\,kg\,m^{-3}$ to $1,920\,kg\,m^{-3}$, equal to the uncompressed values for Pluto and Triton. Future Cassini observations of the regular saturnian satellites may better characterize the existence and nature of surface refractory organics, particularly on Iapetus, whose dark component might well be or include a refractory organic phase.　□

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Manipulating spin and charge in magnetic semiconductors using superconducting vortices

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The continuous need for miniaturization and increase in device speed[1] **drives the electronics industry to explore new avenues of information processing. One possibility is to use electron spin to store, manipulate and carry information**[2]**. All such 'spintronics' applications are faced with formidable challenges in finding fast and efficient ways to create, transport, detect, control and manipulate spin textures and currents. Here we show how**