the distribution of electrons emitted from molecules when they are irradiated with ultraviolet or soft X-ray light) and high harmonic generation[11,12] (which studies the burst of ultraviolet or soft X-ray light emitted from molecules when they are irradiated with intense, near-infrared laser pulses).

All of these technical developments, however, suffer from the same problem — averaging over stereoisomers and molecular orientations, leading to a blurring and potential loss of information. An analogy can be made with X-ray diffraction in crystals: the random orientation of crystallites in powder diffraction obscures the detailed information that is obtainable from single-crystal diffraction. Unless this averaging problem is seriously addressed, the new ultrafast techniques for studying molecular dynamics may not live up to their promise. Filsinger and colleagues' spatial selection of stereoisomers is therefore a step towards the full implementation of techniques that aim to illuminate the molecular processes that transform the worlds within and around us. ■

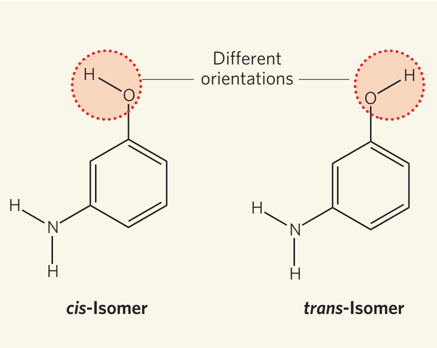

Figure 2 | The same, but different. 3-Aminophenol exists as two stereoisomers — *cis*- and *trans*-isomers — which differ only in the orientation of the oxygen–hydrogen bond (highlighted). The isomers are difficult to separate, but Filsinger *et al.*[1] have done so by deflecting a molecular beam of 3-aminophenol in an electric field.

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SOLAR SYSTEM

Saturn's colossal ring

Matthew S. Tiscareno and Matthew M. Hedman

A hitherto undetected disk of debris around Saturn is the largest ever found to be orbiting a planet. This ring may hold the key to one of the most enigmatic landscapes in the Solar System.

On page 1098 of this issue, Verbiscer and colleagues[1] report the discovery of an enormous ring around Saturn. The authors found this most tenuous of Saturn's known rings, which covers some 10,000 times as much area as the planet's photogenic main rings, by using the Spitzer Space Telescope to detect the ring's faint glow in the thermal infrared region of the electromagnetic spectrum. The ring is composed of dust, probably derived primarily from Saturn's distant moon Phoebe. Its discovery lends support to an earlier theory that dusty material from Phoebe is responsible for colouring the two-toned moon Iapetus.

This 'Phoebe ring' of Saturn (Fig. 1) is similar to previously known tenuous rings in the outer Solar System, such as Jupiter's gossamer rings or Saturn's E ring, in that it is composed mainly of small particles (less than 100 micrometres across) that must be constantly replenished from larger source bodies such as moons, because such tiny grains are eroded away or ejected from their host planet's orbit on very short timescales (less than 1,000 years). The Phoebe ring, like Jupiter's gossamer rings, probably consists of the dust ejected from moon surfaces by impacts[2]; by contrast, Saturn's E ring is supplied by geysers emanating from the interior of the planet's moon Enceladus.

But the Phoebe ring is vastly different in scale from other dusty rings. It has a core radius (the distance from Saturn at which the ring's density reaches its peak value) that is about 200 times the radius of Saturn and 50 times that of the E ring, the previous record holder for the Solar System's largest planetary ring. Thanks to its huge dimensions, the Phoebe ring is at least ten times more massive than the E ring, despite having a particle number density (20 particles per cubic kilometre) that is tens of millions of times lower[1].

The destiny of all that mass may be the most interesting aspect of the Phoebe ring's discovery. Just as the icy dust in the E ring spreads out from Enceladus and seems to brightly coat the surfaces of Saturn's inner moons[3], so the dust in the Phoebe ring is expected to spiral inward towards Saturn, where much of it would be swept up by Iapetus, the outermost of Saturn's large moons, whose surface patterns are a 300-year-old mystery.

Because Iapetus keeps one face always towards its parent planet, like most moons in the Solar System, it also keeps one face (the 'leading hemisphere') directed towards its direction of motion. Iapetus' leading hemisphere is among the darkest surfaces in the Solar System (its albedo — the fraction of sunlight that is reflected back into space — is about 4%), whereas the opposite ('trailing') hemisphere and the poles are quite bright. Surfaces of intermediate brightness, however, are almost entirely absent[4]. It has long been considered plausible that dust from Phoebe is the most likely cause of Iapetus' curious coloration[5,6], but broad agreement has been elusive. The spectral match between the two is not exact, and it is unclear whether the differences can be explained by dust deposition at hyper-velocity and subsequent mixing with the native Iapetan surface.

Furthermore, the lack of dark material at Iapetus' poles is unexpected under a simple model of infalling pollution, although this might be explained by a model that includes infall plus subsequent thermal processing. On the other hand, the leading alternative theory — that the dark material somehow comes from within Iapetus — has a difficult time explaining the close alignment of the dark terrain with the leading hemisphere. Verbiscer and colleagues' discovery[1] of a disk of material surrounding Saturn, corresponding to Phoebe's orbit, is strong evidence for an external source for the dark material on Iapetus. However, much work remains to be done to determine the origin and fate of the observed dust.

As it spirals inward, some fraction of the Phoebe ring's dust makes it past Iapetus and continues on towards the next likely targets, the moons Hyperion and Titan. But the chaotic rotation of Hyperion[7] would cause it to become evenly coated with the ring's dust, not asymmetrically as for Iapetus, and for Titan the infall would be just one more component of its already complex surface chemistry[8].

Further observations of this enormous ring would be highly desirable to better determine its structure and spectral properties. In particular, complementary photometry (measurement of an object's brightness) in visible light would constrain the size distribution and albedos of its component particles — are they really as dark as their presumed source (Phoebe) and destination (Iapetus' leading hemisphere)? Furthermore, such observations could clarify whether other moons besides Phoebe are supplying this ring with dust. Phoebe is by far the largest of Saturn's distant moons, but this does not necessarily make it the best source of dust. Although bigger moons present larger targets for dust-generating impacts, their increased surface gravity correspondingly holds on to

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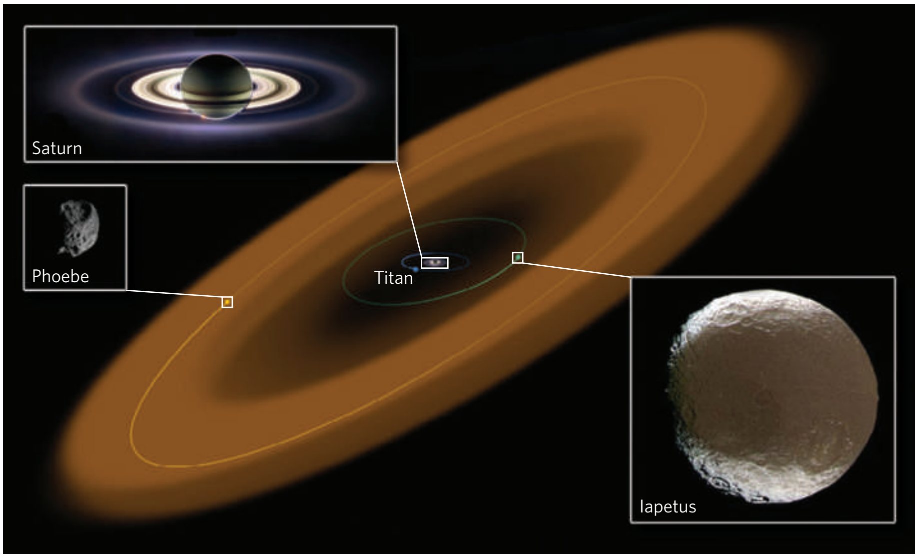

Figure 1 | Saturn's huge ring. This diagram depicts the newly discovered[1] 'Phoebe ring' around Saturn, which spans at least 25 million kilometres and is the largest ring known to be orbiting a planet. The ring corresponds closely to the orbit of Phoebe, the largest of Saturn's outer 'irregular moons', and apparently the source of most of the ring's material. The ring is tilted owing to the influence of the Sun. Dust in the ring probably spirals inward and hits the leading hemisphere of the moon Iapetus, triggering that moon's distinctive two-toned coloration. Also shown are the orbit of Saturn's largest moon Titan, the planet itself and its other rings.

a greater fraction of ejecta, so the best-sized moon for making dust is not obvious[2].

The data presented by Verbiscer *et al.*[1] provide good evidence that this newly discovered ring does in fact ultimately originate from Phoebe in particular: the ring's vertical profile (seen nearly edge-on from Earth) exhibits a double-layered structure whose thickness corresponds to the vertical distance spanned by Phoebe as it goes along its inclined orbit. This structure is very similar to that of Jupiter's rings and just the sort of profile expected for a population of dust particles originating from Phoebe[2]. It may be, as Verbiscer *et al.*[1] argue, that Phoebe's contribution has been enhanced by primordial large collisions[9,10] that generated centimetre-sized and larger chunks of ice and rock that can remain in place over the age of the Solar System. These chunks in turn would generate dust that is ultimately derived from Phoebe and that preserves its orbital characteristics. However, it may well be that Phoebe's little brothers and sisters among Saturn's distant moons also play a significant part in generating the dust that makes up the observed ring, and thus in determining the chemistry of Iapetus.

Whereas nearly everything in the Solar System rotates and orbits in an anticlockwise direction as seen from above, the Phoebe ring almost certainly rotates backwards ('retrograde'), the first ring known to do so. It is also the first ring known to be significantly tilted (by 27°) to its parent planet's equator. Both of these characteristics are due to the ring's source bodies, Saturn's distant moons, many of which (including Phoebe) have retrograde orbits that are more affected by the Sun than by Saturn's equatorial bulge.

The possibility of giant rings existing around other planets is also worth exploring. Jupiter's moon Himalia is only slightly smaller than Phoebe, and whereas Callisto's coloration is less extreme than Iapetus' in both contrast and distribution, Callisto does have bright and dark terrains, and shows spectral differences between its leading and trailing hemispheres[11]. Future observations may therefore reveal giant rings at Jupiter and elsewhere, or may show that Saturn's giant ring is as unique as its more famous main rings. ■

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CLIMATE CHANGE

Early survival of Antarctic ice

Damien Lemarchand

Analyses of boron isotopes in ancient marine carbonate sediments provide an enlightening perspective on the links between carbon dioxide and ice-cap cover at a climatically momentous time in Earth's history.

On page 1110 of this issue, Pearson *et al.*[1] report how they have peered back to a time, around 33.5 million years ago, when Earth underwent a drastic interval of climatic change associated with the formation of the Antarctic ice cap. The authors' work provides a fund of data about the connection between climate and atmospheric levels of the greenhouse gas carbon dioxide.

Coupled records of past variations in temperature and atmospheric CO_2 are precious: they provide fundamental information on climate dynamics that can help in predicting future change. These records are available for recent times from instrumental measurements and, going further back, from data provided by oxygen isotopes in ice cores and by CO_2 trapped in air bubbles in such cores. The ice-core data take us back almost a million years[2,3], but that still covers only the last few glacial–interglacial cycles, which were characterized by atmospheric CO_2 concentrations of 170–300 parts per million by volume (p.p.m.v.) — lower than the present-day value of about 380 p.p.m.v.

To test climate theories in the present-day condition of massive carbon emissions to the atmosphere, what is needed is access to geological archives that provide clues about how past climate responded to CO_2 levels higher than those of today. Analyses of oxygen isotopes in the shells of marine organisms that form carbonate sediments can provide proxy data on ancient global temperature and ice volume, in the same way that oxygen isotopes in ice samples provide such data for more recent times. But, so far, reconstructions of ancient levels of CO_2 have been rare[4], and they remain much needed.

This is where Pearson *et al.*[1] come in. They have used boron isotopes in exceptionally well-preserved marine microfossils — the carbonate shells of organisms called foraminifera — as an indirect measurement of atmospheric CO_2