Protective Shields in the Solar System

Snow formed from iron or metallic hydrogen – both of these phenomena can drive magnetic fields. Measuring them provides researchers with insights into the processes that change the internal mechanisms of the planets. **Ulrich Christensen**, Director at the **Max Planck Institute for Solar System Research** in Göttingen, investigates the broad diversity of these magnetic fields.

TEXT **THORSTEN DAMBECK**

In the 1950s, radio astronomy was still in its infancy. But the observatories were by no means small – quite the opposite, in fact: the astronomers strained their ears for celestial radio sources on enormous, open spaces. In 1955, US researchers made a lucky find with such an installation near Seneca in the US state of Maryland, where more than eight kilometers of antenna wire had been erected. While observing the Crab nebula 6,300 light-years away, this monster of an antenna detected a transmitter that was much, much closer, and that interfered every now and then in the short wavelength range: Jupiter.

On its journey through this constellation, the planet had reached just the right position for its interfering action. Very soon the astronomers received further radio emissions from it, this time at higher frequencies and almost constant over time. A consistent picture emerged: In order to manage all this, Jupiter had to be surrounded by a magnetic field – because the high-frequency waves originate from electrons hurtling around the giant planet, trapped in its magnetic field. The first planetary magnetic field beyond Earth had been found.

Today, on-site measurements are expediting the research into Jupiter's magnetic field. Since 1973, eight space probes have made their contribution to this, and further missions are en route or in the planning stage. The robotic discoverers have been lucky on other planets, as well: Saturn, Uranus and Neptune also have global magnetic fields, as does the smallest planet, Mercury. The properties of these fields are quite different, though.

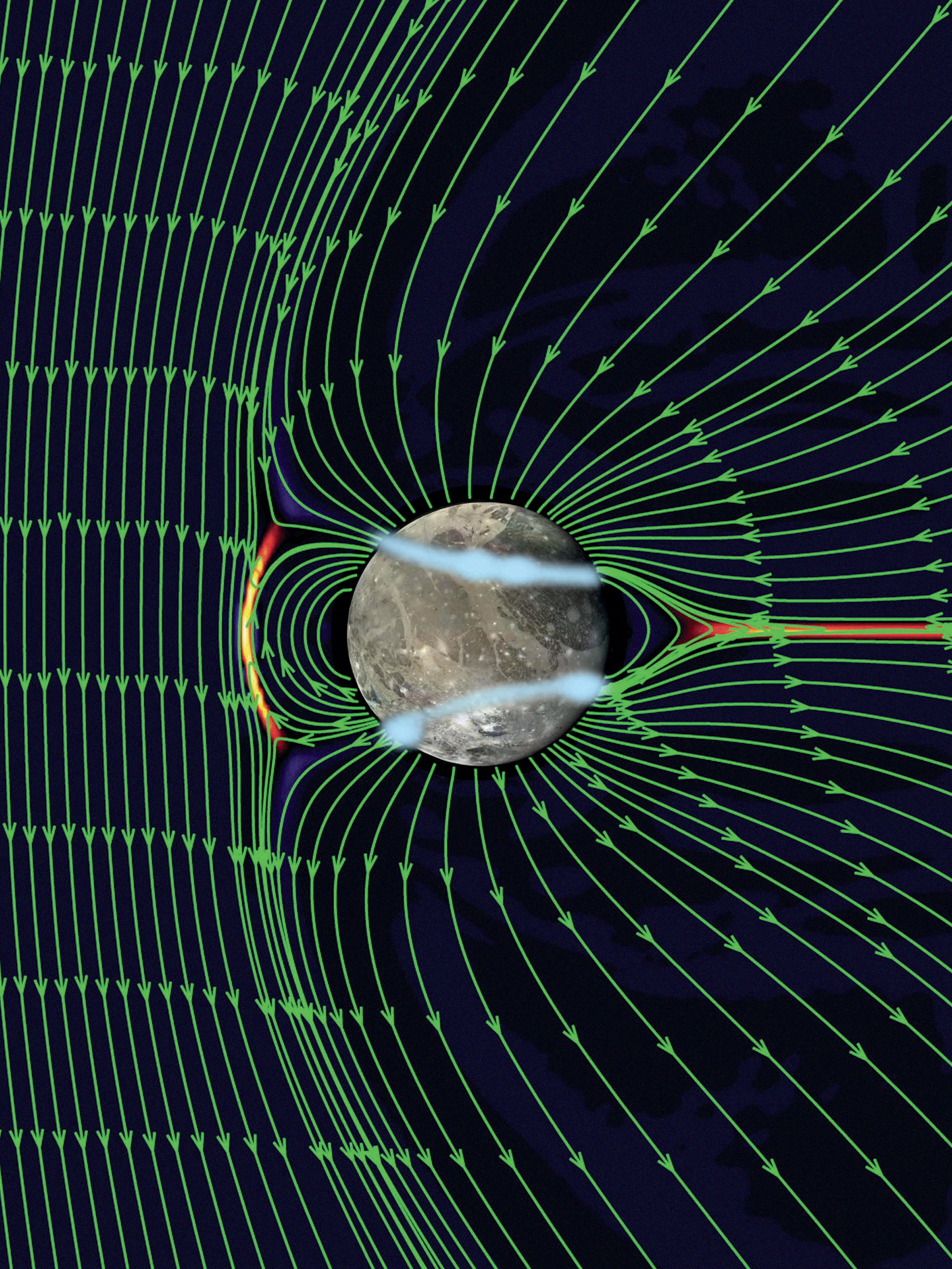
A RAPID ROTATION AIDS THE DYNAMO EFFECT

"There is a confusing diversity," says Ulrich Christensen. The globes of the celestial bodies are lined up in the window of his office at the Max Planck Institute for Solar System Research in Göttingen: Earth's moon and Mars, neither of which, according to the space probes, currently has a global magnetic field. Venus also has a window seat. The planet has long been called "Earth's sister" – but unlike our home planet, it also has no magnetic field of its own.

So what distinguishes these planets from the magnetic planets? "Celestial bodies without a magnetic field lack an active, planetary dynamo," says Christensen, who is an expert on the numerical simulation of such dynamos. All global magnetic fields originated deep below the surfaces of the planets. "This is where flows have to set electrically conductive liquids in motion. A sufficiently rapid intrinsic rotation is also very helpful for a dynamo process." This is lacking in Venus, for example, which requires no fewer than 243 terrestrial days to rotate once about its own axis. Jupiter completes a rotation in less than ten hours; its magnetic field resembles that of Earth in some respects. Although it is more than ten times stronger, researchers basically measure a simple dipole field like that on Earth, comparable, in a sense, to a gigantic bar magnet. The field is also inclined by around ten degrees with respect to the planetary

Special status: Ganymede is the only moon to have its own small magnetosphere. It lies in the middle of the Jovian field lines, which deform close to the moon and partially mix with those of Ganymede. Where the field lines open up, particles from Jupiter's magnetosphere penetrate into the thin atmosphere and generate polar lights, also called aurorae.

Graphic: Xianzhe Jia, University of Michigan (based on AGU publication JGR, 113, 6212, 2008)



axis of rotation. This doesn't, however, mean that the same processes occur in Jupiter's interior as in the Earth's, because, being a gas giant, its structure is completely different.

The role played by the liquid iron whose currents in Earth's core give rise to our magnetic field is adopted in Jupiter by hydrogen – the substance of which the planet is largely composed. But it is a different hydrogen than the one we know. The high pressure to which the element is exposed in the interior of the planet has a radical effect on its properties.

Not only are the atoms squeezed together so closely that they form a liquid, but most importantly, their electrons are no longer limited to their former home atoms, but can migrate almost at will: the insulator thus becomes a metal. This is indicated not only by theoretical computations, but by laboratory experiments as well – for example at the Max Planck Institute for Chemistry in Mainz. The researchers there put hydrogen under great pressure until it reaches values similar to those that occur in the interior of gas planets. In 2011, they registered an increase in the electrical conductivity at several million bars.

JOVIAN MOON GANYMEDE IS LARGER THAN MERCURY

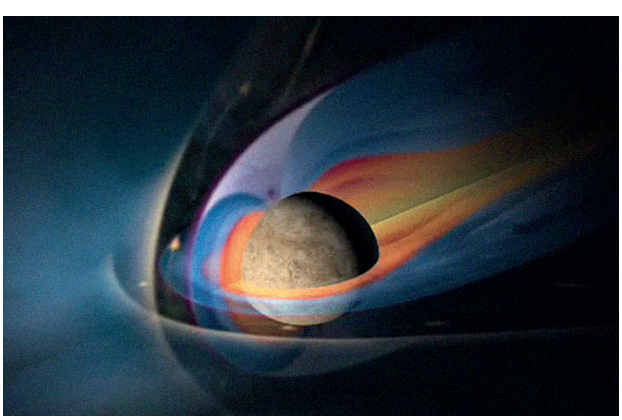
The largest planet is also the focus of Johannes Wicht's work. A staff member at the Max Planck Institute for Solar System Research, he hit on a double structure that he described recently with his colleague Thomas Gastine in GEOPHYSICAL RESEARCH LETTERS: "Our simulations show that the earth-like component of the magnetic field is generated in the depths of the atmosphere," explains Wicht.

In addition to this, there is a second dynamo process that occurs at the transition to metallic hydrogen. The magnetic field of the gas giant may appear to be similar to Earth's, but it has its origin in exotic processes.

A total of 67 known satellites orbit Jupiter – a kind of miniature solar system. With Ganymede, it plays host to the largest of all moons; its diameter is 5,268 kilometers, making it larger than the planet Mercury. Between 1995 and 2003, the American *Galileo* space probe

THE SUN'S MAGNETIC NEIGHBOR

On the outside, it resembles the moon, but below its surface, Mercury, the closest planet to the Sun, is different from all other bodies in the inner solar system. Particularly strange is its huge metal core, which takes up 83 percent of the planet's radius (comparative value for the Earth: 54 percent). Its magnetic field is also peculiar. It has long been known that its strength is just one percent of the strength of the terrestrial field.



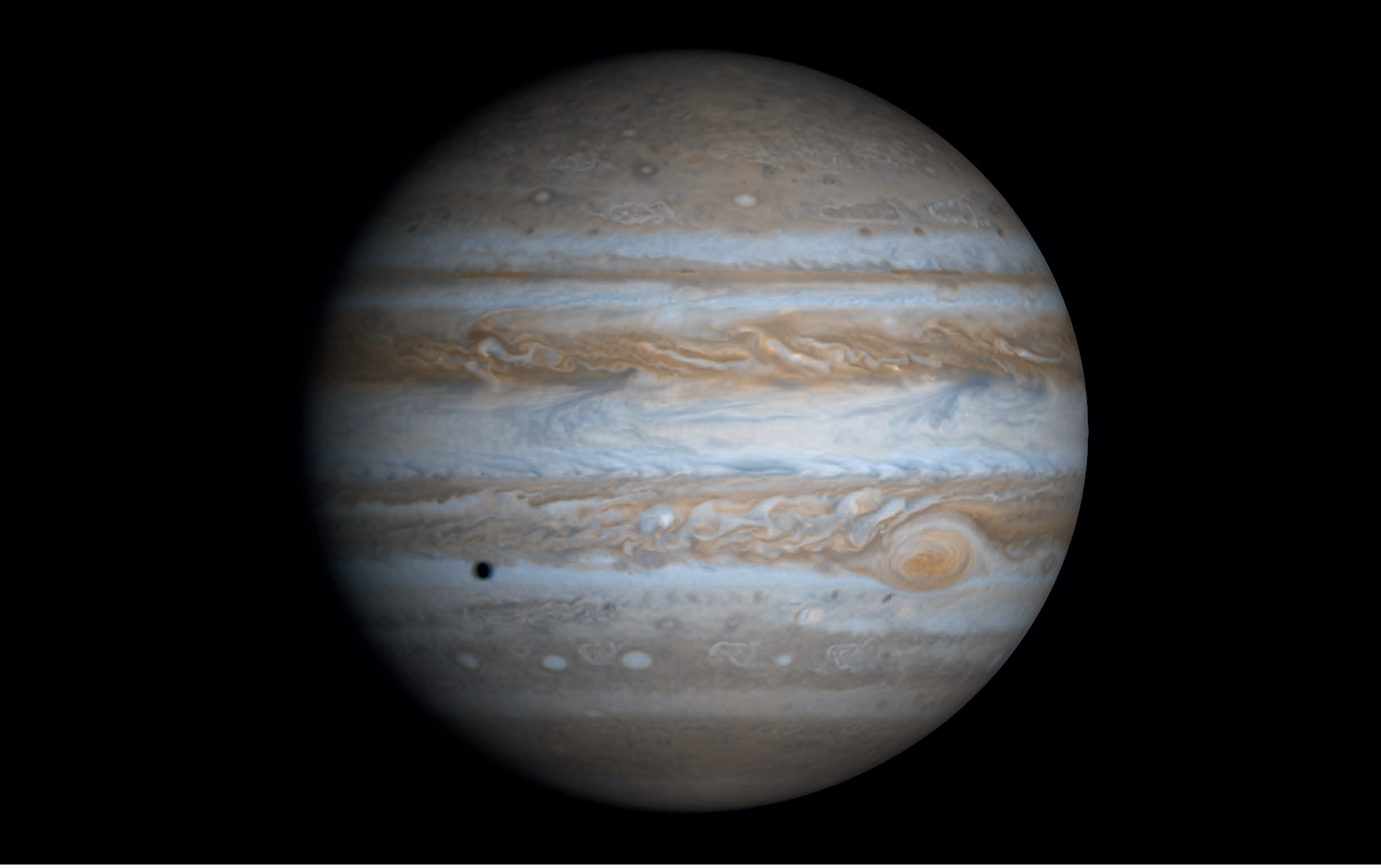
A model of Mercury's magnetic field: The depiction is based on the data of the first fly-by performed by the *Messenger* space probe. Registered and imaged is the region of charged particles that arises through interactions with the solar wind.

"Recently, NASA's *Messenger* probe measured a significant northward shift of the magnetic equator compared with the geographic equator – a shift amounting to 20 percent of the planet's radius," explains Johannes Wicht from the Planets and Comets Department at the Max Planck Institute for Solar System Research in Göttingen. "This north-south asymmetry is as surprising as it is unique, because apart from that, Mercury's magnetic field has a very simple structure and is almost rotationally symmetric." It's as if a bar magnet had simply been shifted toward the north.

In a current study, Wicht and his team have analyzed several dynamo models in order to find the reason for Mercury's special magnetic characteristics. "In a very similar way to the processes in Ganymede, iron snow could play an important role for the dynamo in Mercury," explains the scientist.

The snow drives the dynamo with such force that the magnetic field generated is small scale, and the north-south symmetry is broken sufficiently. At the same time, the iron snow leaves behind a thick layer of sulfurous material under the rocky crust, which doesn't participate in the dynamo process. It acts like a filter that allows only the simpler components of the magnetic field to penetrate through to the surface.

Photo: NASA/University of Michigan/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington



explored the Jovian system and the giant moon also appeared several times on the schedule of visits.

It was during these visits that *Galileo's* magnetometer discovered a unique feature that characterizes the moon to date: Ganymede is the only moon to have a global magnetic field – and it is three times stronger than that of the planet Mercury ("The Sun's magnetic neighbor," left-hand page). A recently published study by Ulrich Christensen in the journal Icarus provides a look into Ganymede's interior. "As on Earth, the source of the magnetic field is a liquid core," says the Max Planck Director. At the same time, he rejects older ideas that the saline subsurface ocean, a feature of both Ganymede and its neighboring moon Europa, could be where the dynamo effect takes place.

"Ganymede's core probably also contains quite a bit of sulfur," says Christensen. This isn't unusual, it is assumed that Earth's core also contains up to 10 percent of lighter substances, probably a mixture of sulfur, oxygen and silicon, in addition to the metallic components. The processes in Ganymede's core, which Christensen has modeled, appear to be bizarre neverthe-

Striped gas giant: Jupiter is the largest planet in the solar system, with an equatorial diameter of 142,984 kilometers. The picture above shows it in its natural colors with the shadow of its moon Europa (left). The diagram below illustrates the shapes and sizes of the magnetic fields of the Earth (top left) and Jupiter. The form of the terrestrial magnetic field is determined essentially by the solar wind, and that of Jupiter by the volcanic activity of its moon Io, whose particles constantly feed the magnetosphere and form the magnetic field lines into a so-called current layer.

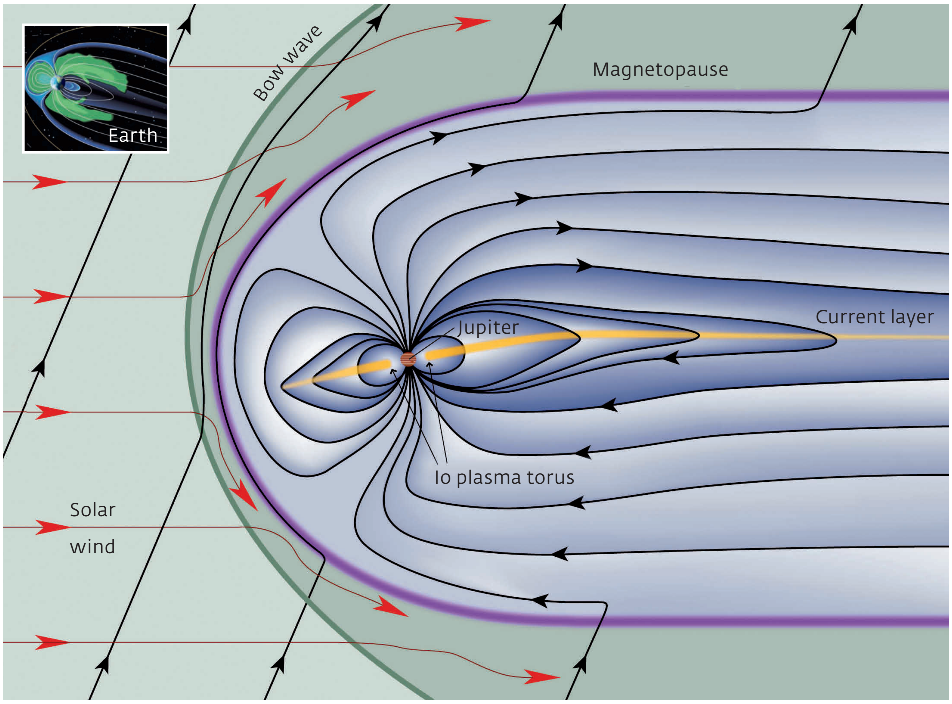


Photo: NASA/JPL/University of Arizona, graphic: Fran Bagenal & Steve Bartlett

Investigates the magnetic fields in the planetary system: Ulrich Christensen, Director at the Max Planck Institute for Solar System Research in Göttingen.

less: they involve a kind of snow whose "flakes" consist, not of ice, but of iron.

Before he embarks on a mental excursion into this exotic world, the researcher calls to mind the center of our own planet: It is known that there is a solid iron-nickel core here. This grew in size by slow cooling over the course of Earth's history – first in the center, due to the high pressure; scientists call this "freezing out." Above the core is a molten zone that completely surrounds the solid inner core. This is the liquid story of the terrestrial metal core, where the convection currents are found.

"Convection currents can be triggered not only by temperature gradients, but also by a difference in chemical concentrations," says Ulrich Christensen. Although the freezing out of iron is also important on Ganymede, the simulation calculations say its iron core has a different structure: "The pressure there is much lower than in Earth's core. It is therefore probable that the core of this moon freezes first on the outside, and the denser iron flakes fall softly like snow, namely toward the center. However, the temperatures here increase, and the iron snow melts again."

MODEL CALCULATIONS COME QUITE CLOSE TO REALITY

There is thus a downward net flow of iron in the metal alloy. This results in a stable liquid layer forming above, which contains less iron, but more sulfur instead. These differences in concentration trigger the convection current, which in turn drives Ganymede's dynamo. Christensen says that this chemical convection is more important than thermal convection in smaller planetary bodies. "In Ganymede's core, it likely at least dominates, and it may even be the only form."

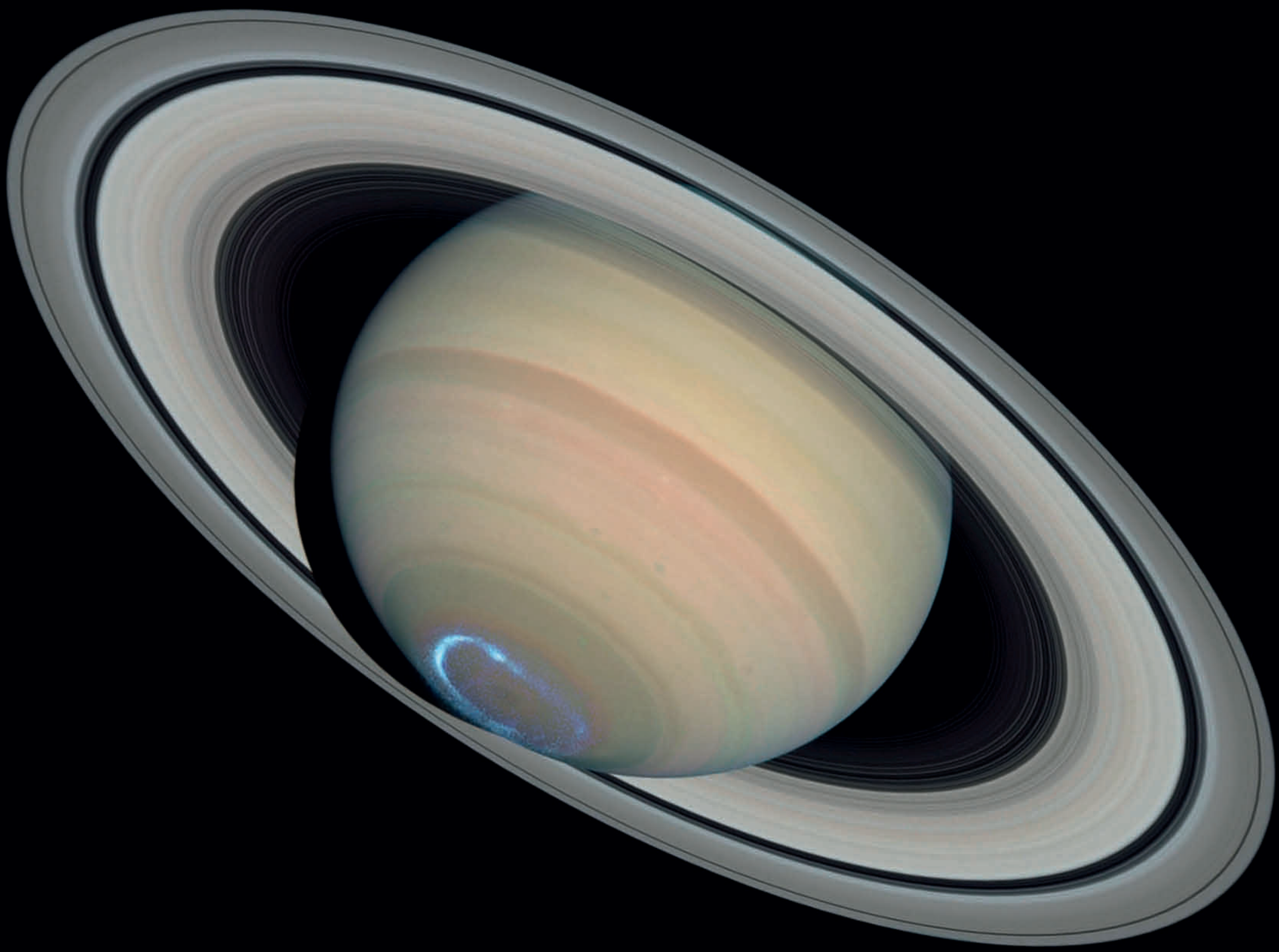
The model calculations carried out by the researcher reproduce the global magnetic field measured by *Galileo* quite well – particularly the rather small contribution made by higher-order fields to the total field. Christensen admits that the probe was able to contribute only a few measurements during its brief fly-by, but he is looking forward to new data that the *Jupiter Icy Moon Explorer (Juice)* is expected to provide. The European Space Agency will send this heavyweight mission off on its journey in 2022, with a planned arrival date in 2030.

The last stage will be for the ESA probe to change course and enter into an orbit around Ganymede from where it will, among other things, measure its magnetic field in detail. A further innovation: the planetary researchers will focus their sights on the interaction between the unequal magnetic dynamos of Ganymede and Jupiter.

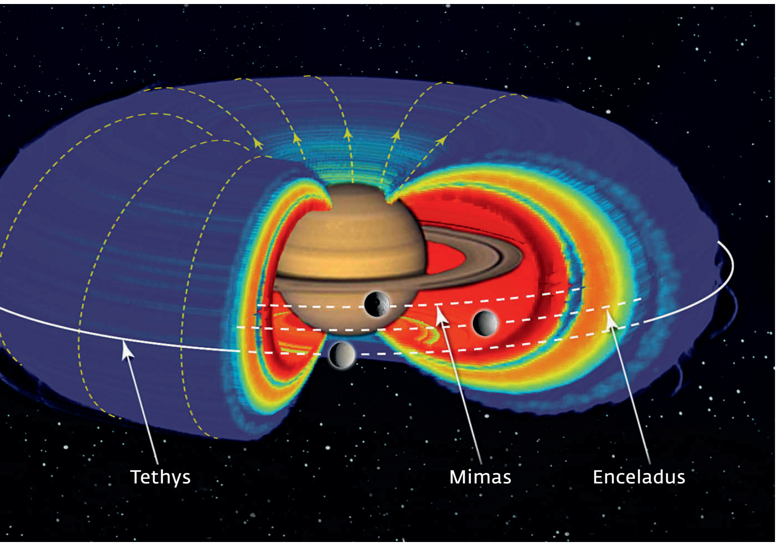
Jupiter's magnetic field dominates an enormous region around the gaseous giant: its magnetosphere. Next to that of the Sun, it is the largest structure in the planetary system. "It can even still be detected at Saturn," says Norbert Krupp, who has studied the magnetospheric processes of both gas planets. As a team member of the *Cassini* mission, the Göttingen-based Max Planck scientist has been in the front row of the investigation of Saturn's system for a decade.

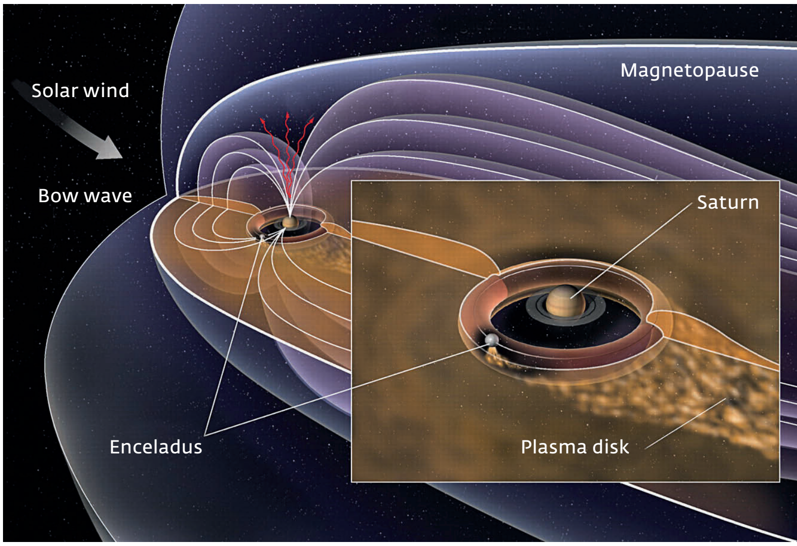
"Saturn's magnetosphere resembles a huge aerodynamic body, with the ringed planet being located in its head," says Krupp. At the front end, the charged particles of the solar wind strike this magnetic shield, where they are abruptly decelerated and deflected in a wide arc around the planet. Depending on the strength of the solar activity, this takes place 20 to 35 Saturn radii from the planet.

At the opposite end, the magnetosphere forms a long "tail," the "magnetotail." It is believed that this extends hundreds of Saturn radii into space. The form of Saturn's magnetic field thus resembles that of the magnetic fields of Earth and Jupiter, with its magnitude ranging somewhere in between.



Ringed sphere: The planet Saturn with its extended system of rings is already a fascinating sight in the small telescope. The *Hubble* space telescope reveals fine details, such as a light blue structure around one of the poles (image above). This is an aurora that emits UV light and is associated with the magnetic field of the planet. Like the magnetic fields of Earth and Jupiter, this one (graphic below right) resembles a giant aerodynamic body, with the ringed planet being located in its head. The spatial region of the field is fed with particles that are constantly released by the moon Enceladus. The moon orbits Saturn together with others, such as Tethys and Mimas, in a plasma torus of positively charged particles (graphic below left).





Discussions in a small group: Thomas Gastine, Johannes Wicht and Markus Fränz (from left).

The most obvious proof of the magnetic activity on the ringed planet is offered by light phenomena in its northern and southern polar regions: the aurorae. Just like on Earth, they occur when solar wind particles that were trapped in Saturn's magnetic field spiral down along the magnetic field lines to the magnetic poles, colliding with molecules of the atmosphere in the process. Unlike our polar lights, Saturn's aurora doesn't radiate in visible light, but at ultraviolet wavelengths. And while high levels of polar light activity are typically over after a few hours on Earth, on Saturn they can sometimes be observed for days.

SEVERAL CIRCUITS IN THE MAGNETIC FIELD BOOST ENERGY

Saturn's magnetosphere is the venue for high-energy processes, as it is filled with fast-moving particles. These originate mainly from Enceladus: the geologically active mini-moon ejects 100 to 300 kilograms of water vapor and ice particles per second, some of which can leave the moon's weak gravitational field. "The H_2O molecules are ionized by the solar UV radiation and accelerated in the magnetic field. They can be encountered outside of Enceladus' orbit in the whole magnetosphere," says Norbert Krupp.

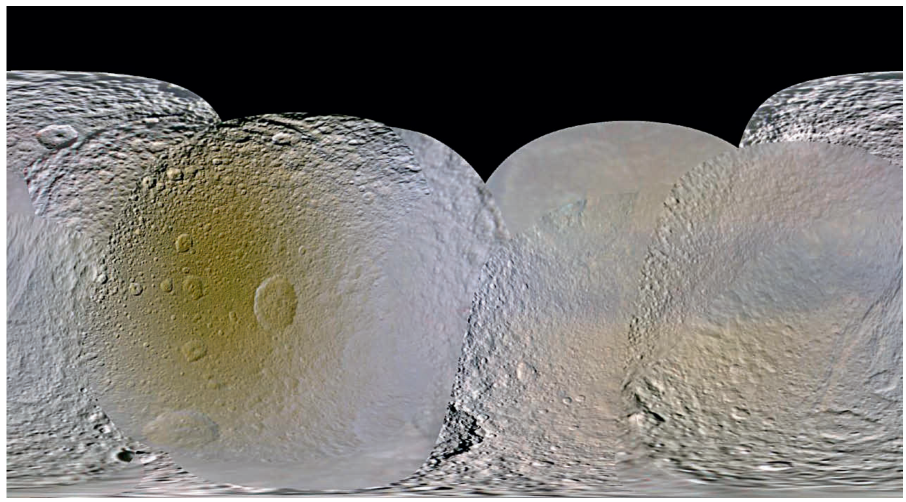
Primarily protons and electrons, which can attain energies of up to 100 mega-electronvolts (MeV), collect in a number of radiation belts. "How exactly they achieve this is still the subject of intensive research. They may have already done several circuits in the magnetic field when they hit the detectors with such energy," explains Krupp. The absorbing effect of the rings and the inner moons means that these belts aren't as distinct as their terrestrial counterpart, the Van Allen belt.

The moons of Saturn are exposed to the particles as they rain down. Norbert Krupp and his colleague Elias Roussos are therefore also investigating what effect the constant bombardment of high-energy particles – especially electrons – has on the surfaces of the moons. Experts use the term "space weathering" when they describe the chemical weathering of the surface of a celestial body brought about by the effects of open space.

The latest analyses, recently published in the journal Icarus, indicate that the sides of the ice moons Mimas, Tethys and Dione that face Saturn are being chemically altered by electron bombardment. These electrons have so much energy (a few MeV) that they drift perpendicularly to the magnetic field, but in the opposite direction to the orbital motion of the moons. Simultaneously, they shuttle to and fro between the north and south poles along the magnetic field. Experts can use this pattern of motion to calculate the impact zones on the respective moon. It has been revealed that some of the surface characteristics in the equatorial regions observed by *Cassini's* onboard cameras match the calculated distribution pattern of the particles.

Back to the inner solar system: The red planet allows us to study what happens to a terrestrial planet when its magnetic shield is extinguished, because Mars probably also had an active dynamo at some point: a mosaic of magnetized rock on its surface still serves as a reminder of this magnetic era. Markus Fränz, also from the Max Planck Institute in Göttingen, has eval-

Photo: Ronald Schmidt – AFWK



Scarred by the weather in space: The surface of Saturn's moon Tethys shows clear traces of chemical weathering. The bluish streak in the right half of the image is caused by high-energy electrons that bombard the ground under the influence of the planetary magnetic field.

uated the plasma measurements of the *Mars Express* probe, which has been orbiting Mars since 2003.

Is it still possible to measure how the water of the unprotected planet falls victim to the solar UV radiation and the solar wind? "We measure the decomposition products of the H_2O molecule, so to speak, namely the oxygen ions. Recently we have also been incorporating the measurements of the radar instruments into our analyses," says Fränz. This allows the researchers to obtain a more complete picture, because they also see the lower-energy, cold plasma that remains hidden from the actual plasma instrument.

The ion outflow obtained in this way can be used to do a back calculation to obtain the amount of water initially present, and the result is a dramatic drying up. According to these calculations, the water contained in a global Martian ocean several hundred meters deep escaped into space over billions of years. "The real value is probably even higher since, in its youth, the Sun likely went through phases when it was considerably more active than today and, back then, decimated the water reserves with particular ferocity," assumes Markus Fränz.

What started with Jupiter's radio waves six decades ago has since provided many findings about the planet. And a further rendezvous with the gas giant is already scheduled: a magnetometer (JMAG) will also travel into the Jovian system on board the aforementioned *Juice* probe, and Christensen, Krupp and Roussos in particular are looking forward to receiving its data.

Also on board will be a particle instrument called the *Particle Environment Package (PEP)* incorporating important contributions from Germany. Fränz and his colleagues want to use this instrument to measure the thin gas atmospheres of Jupiter's moons, as well as the neutral particles and ions that romp in the magnetic fields there. Markus Fränz is certain: "The discoveries will continue." ◂

TO THE POINT

- **Although magnetic fields are widespread in space, not all planets in our solar system possess one. Venus and Mars have none.**
- **Even though they are very diverse and have very different structures, all global magnetic fields originate deep below the surfaces of the planets and require an active dynamo.**
- **The Jovian moon Ganymede is thought to be the only moon to have a global magnetic field; it is three times stronger than that of the planet Mercury.**
- **The magnetic fields of the gas planets Jupiter and Saturn are particularly extensive. Jupiter's magnetosphere is the largest structure in the planetary system next to that of the Sun.**

GLOSSARY

Aurora: This phenomenon, which is also called the polar lights, is a luminous phenomenon in the polar regions of a planet. It is caused by particles in the solar wind – mainly electrons and protons – that collide with heavy ions in the upper layers of a gaseous atmosphere where they ultimately cause fluorescence.

Space weathering: Specialist term for the chemical weathering of the surface of a celestial body that has no atmosphere. This type of erosion is caused by effects from open space, such as the impact of micro-meteorites, cosmic radiation or solar UV radiation.

Van Allen belt: A ring (torus) named after American astrophysicist James Van Allen (1914 to 2006) and made up of high-energy charged particles that are trapped by Earth's magnetic field. The belt essentially consists of two radiation zones. Other planets also have similar structures.