Stars with Great **Attraction**

They are some of the most exotic objects in space: neutron stars. Incredibly dense and only 20 kilometers across, they rotate about their axes at breakneck speed, emitting cones of radiation out into space in the process. Some of these cosmic beacons have particularly strong magnetic fields. **Michael Gabler** from the **Max Planck Institute for Astrophysics** in Garching studies these magnetars – and so learns a thing or two about their nature.

TEXT **HELMUT HORNUNG**

On the fifth day of the journey, a huge storm came up, sweeping the boat further and further off course – directly toward the magnetic mountain. Even prayers were of no help: "The force of the mountain began to draw the ship toward it, causing it to break up." The knights in *Herzog Ernst*, a popular German epic from the late 12th century, must battle this danger in addition to fighting terrifying snakes and other monsters that lurk in the depths of the ocean waiting for the seafarers of yore. Terrestrial magnetic mountains are the stuff of fiction – but magnetic stars really do exist.

Magnetic fields are omnipresent in space. They surround planets, permeate our Milky Way, and are present not only in galactic gas, but also in the suns formed from it. Most stars, however, have only very weak global magnetic fields. In the 1950s, astronomers discovered so-called Ap stars. Their atmospheres were found to contain large quantities of metals, such as manganese and chromium. These celestial bodies have two to ten times the mass of our Sun – and a magnetic field that is one thousand times stronger. The Alioth star in the handle of the Big Dipper is part of this family, for example. The researchers also found a few magnetic stars among the white dwarfs, the burnt-out nuclei of conventional stars.

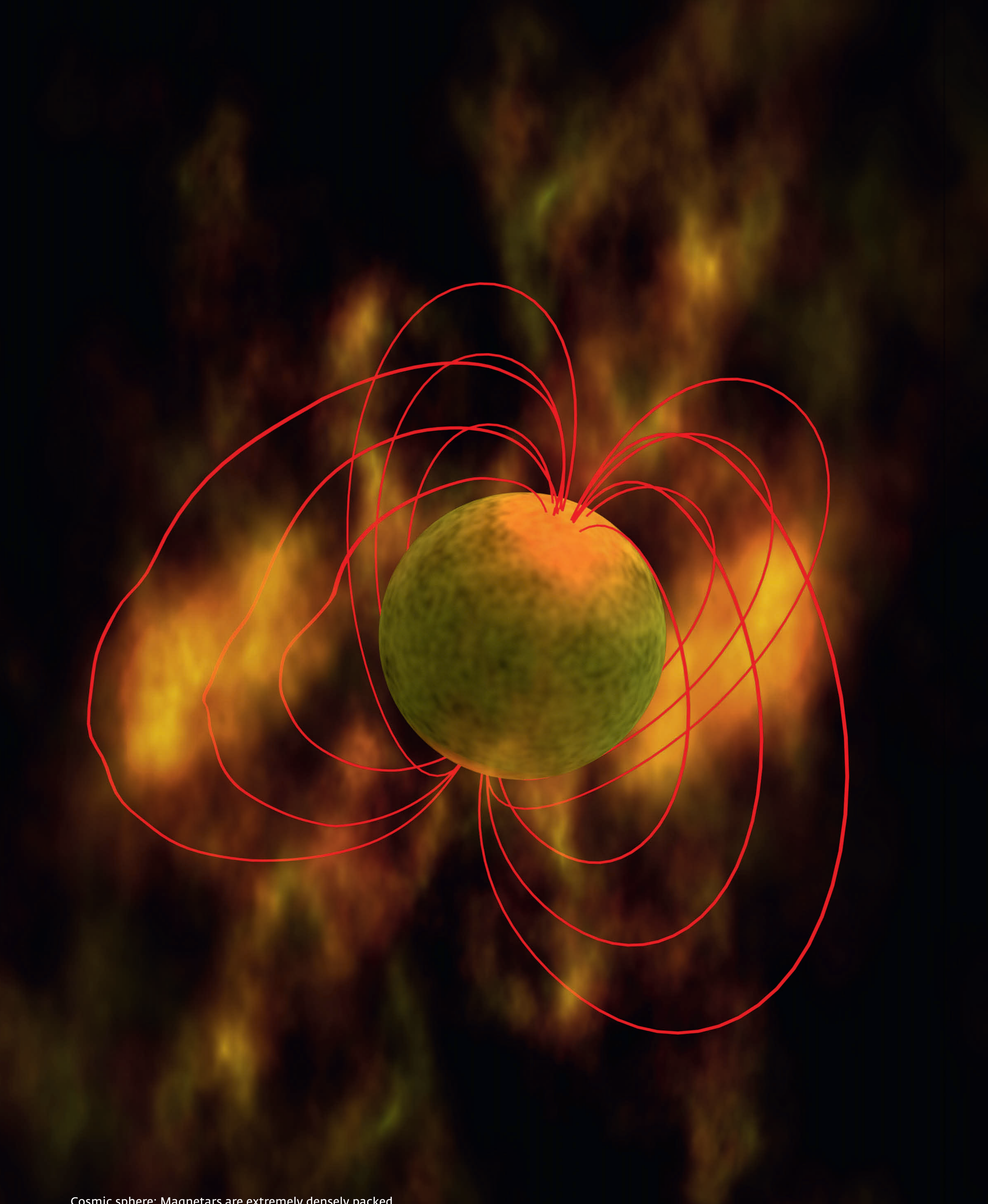
A POTENTIAL HAZARD FOR INTERSTELLAR SPACESHIPS

But the magnetars beat everything. These remnants of supernova measure around 20 kilometers across, are extremely densely packed and rotate very rapidly about their axes. During the birth of this type of neutron star, it is not only the matter that is tightly squeezed together, but also the magnetic field is greatly compressed, and a dynamo effect shortly after the collapse can then amplify this field even further.

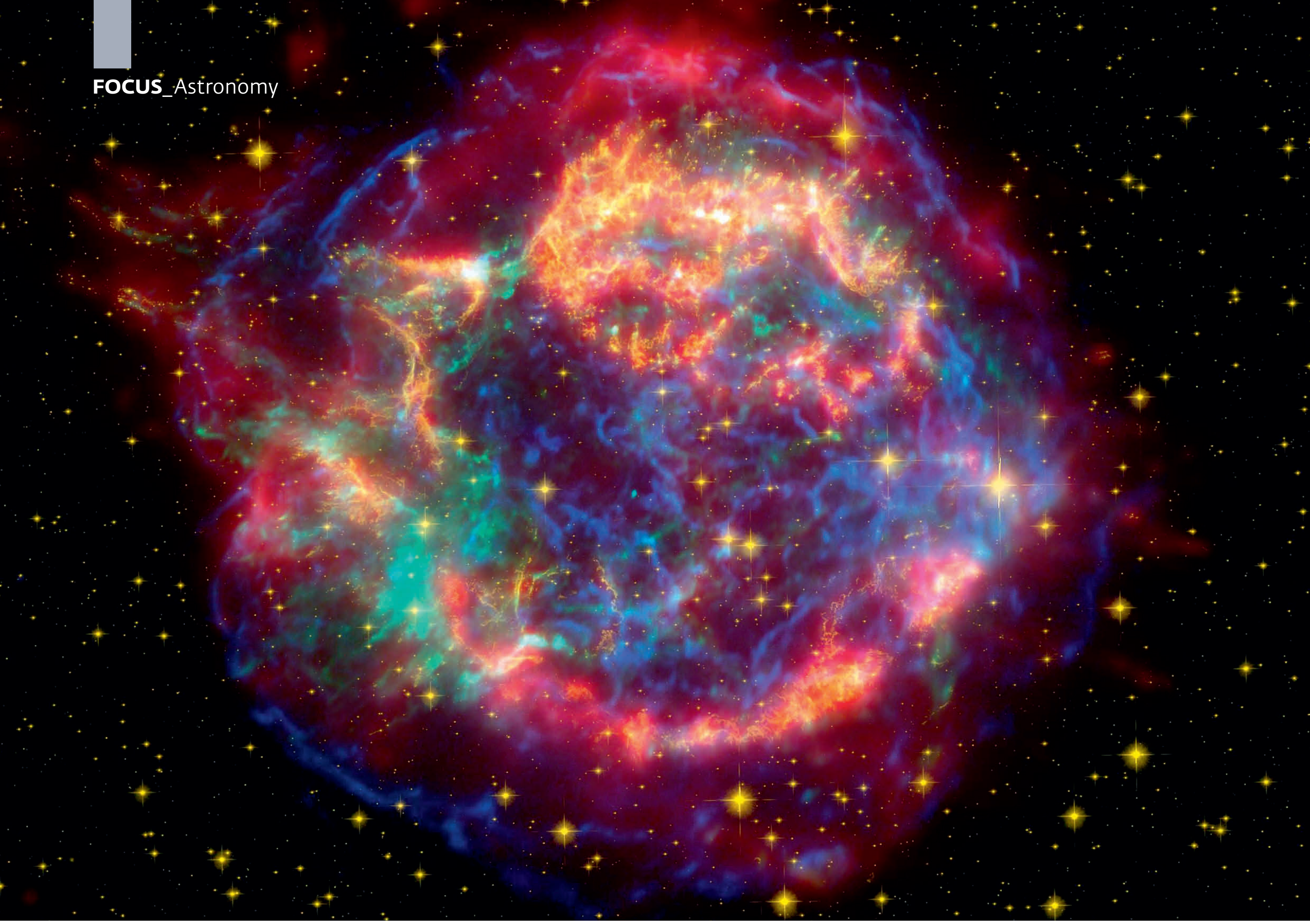
In this way, the corpses of these stars attain field strengths corresponding to those of 100 billion commercial bar magnets. "A magnetar as far away as the moon would delete all the data from the credit card in your pocket," says Michael Gabler. For interstellar spaceships, these stars could thus present a real hazard. However, the researchers at the Max Planck Institute for Astrophysics aren't really interested in fiction, as magnetars are exciting enough for science, as well.

The objects have a turbulent history. They form upon the spectacular death of a sun, a supernova, when a star with a mass of between 8 and 20 solar masses has gotten itself into an energy crisis. The fuel that fed its nuclear fusion over many million years has been spent. Its nuclear furnace is extinguished. The sphere, like an onion, now consists of shells of all possible chemical elements that were created during the fusion. The last step is the formation of an iron core in the center. Density and temperature continue to increase until the atoms of iron effectively vaporize. >

Graphic: NASA



Cosmic sphere: Magnetars are extremely densely packed, rotating neutron stars with unusually strong magnetic fields.



Gravitation exerts an ever-increasing pressure until the point comes when the core, roughly the same size as our moon, can no longer withstand it: it collapses in fractions of a second. Matter plummets toward the center, which is simultaneously compressed even further – until this matter rebounds. Like a spring that is first pressed together and then released, the energy suddenly escapes toward the outside, sweeping the matter along with it into open space. The density in the remaining central sphere of 1.4 solar masses resembles the density in an atomic nucleus. This is the hour of birth of the neutron star. (Although *hour* of birth is much exaggerated, as this all takes places within milliseconds.) The neutron star heats up to temperatures of up to 500 billion degrees and produces vast quantities of neutrinos.

These neutrinos – electrically neutral particles with an extremely low mass and hardly any interaction with matter – are crucial to the explosion process, because the shock wave that races outward and is supposed to tear the star apart actually fizzles out after just a few hundred kilometers. The neutrinos, on the other hand, carry so much energy from the core to the shock wave that the star's outer layer is ultimately hurled away after all. A supernova flares up.

A SUPERNOVA EXPLODES IN THREE DIMENSIONS

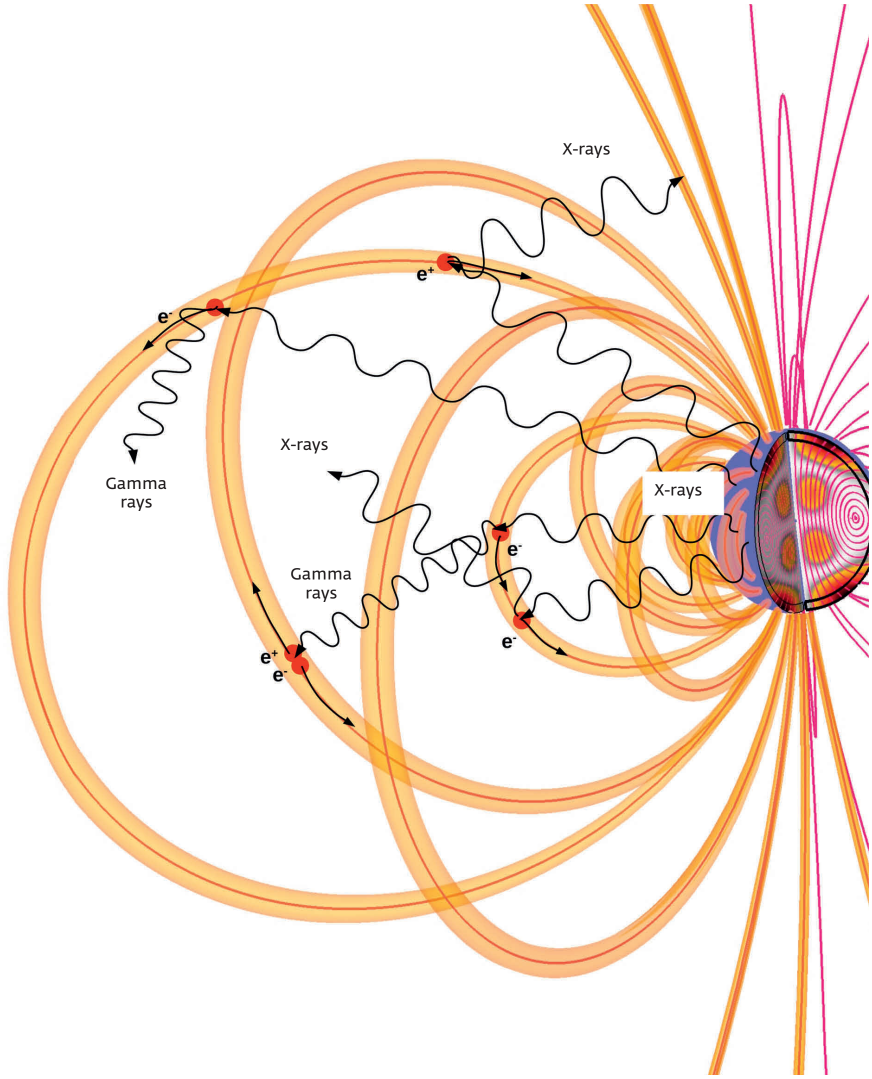
The exact scenario of such a cosmic catastrophe with neutrino heating is much more complicated and is the subject of intensive research, also at the Max Planck Institute for Astrophysics in Garching. The scientists there use supercomputers in their attempts to model stellar explosions. In 2014, a group led by Thomas Janka was the first to succeed in simulating a supernova in three dimensions with all physically important effects.

Michael Gabler deals with what remains after the blazing inferno: the neutron stars. "Their properties can't be reproduced in a laboratory on Earth," he says. The density alone surpasses that of an atomic nucleus. And a piece of stellar matter the size of a sugar cube would weigh no fewer than one billion tons on Earth.

What is the structure of a neutron star with the same diameter as a city the size of Munich? Which interactions do the smallest constituents of stellar matter experience – that is, neutrons, protons and electrons, but also such exotic particles as pions, kaons and quarks? "In order to get answers to these questions, we have to understand the structure of a neutron star," says Gabler. And this is where the magnetars come in handy.

These objects are the most powerful magnets in the universe. The magnetic fields on their surfaces reach values of up to a few quadrillion gauss. By way of comparison, the terrestrial magnetic field tips the scales at a mere one gauss, and magnetic fields of at most ten million gauss can be generated in the laboratory. But there is one

Photo: NASA/JPL-Caltech/STScI/CXC/SAO



Left-hand page: Worst-case scenario in space: When a massive star has spent all its fuel, it collapses and is literally torn to pieces in the ensuing explosion. The remnant of such a supernova is shown by this false-color image, which is a combination of images in the X-ray and infrared ranges, and in the visible range. The light from the object known as Cassiopeia A reached Earth around 1680.

This page: Neutron stars – and magnetars in particular – are surrounded by strong magnetic fields. Electric currents (yellow) comprised mainly of electrons (e^-) and positrons (e^+) flow along the field lines (magenta). These charge carriers scatter the X-rays emanating from the surface of the star. The high-energy gamma radiation that occasionally arises as a result can produce further electron-positron pairs.

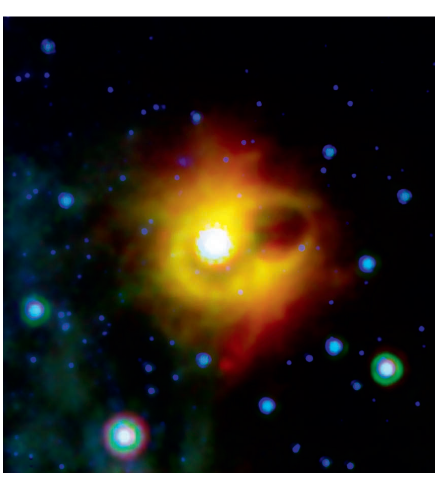
similarity between Earth and the magnetars: both have a strong magnetic dipole field. And the generation of both of these fields is based on the dynamo effect, which in turn is caused by the motion of conductive matter. In the case of Earth, this is mainly the liquid iron in the core; with the neutron star, it's the ultra-dense matter. "The stars are very hot. The neutrinos carry the energy away, creating a great deal of internal dynamic activity," says Gabler.

What's more, the precursor star also had a more or less strong magnetic field that was compressed during the collapse and baked into the neutron star, as it were. The rotation plays an important role as well, as the stellar dipole emits energy that it acquires from the rotation. This is why a neutron star can be observed in the first place. If this were not the case, a 20-kilometer object a few hundred or a few thousand light-years away couldn't be observed at all, even with the best telescopes.

Along the axis of the magnetic field, the rotating neutron star emits a narrowly focused cone of radiation. Similar to a lighthouse, this cone sweeps through space. If, in the process, it sweeps across the line of sight to Earth, astronomers observe a rhythmic flashing whose frequency corresponds to the rotational period of the star. In 1967, Jocelyn Bell in England accidentally discovered the first of these objects.

Today, the researchers are aware of more than 2,200 of these pulsars. Their radiation covers the entire electromagnetic spectrum and ranges from radio waves to gamma rays (MaxPlanckResearch 4/2013, p. 48 ff.). Around 10 percent of all neutron stars observed belong to the magnetar family. However, these occur only as very weak pulsars. The reason for this lies in their rotational speed: "From their pulse frequency we can deduce that magnetars usually rotate very slowly, unlike many other neutron stars," explains Michael Gabler. The values range from two to ten seconds per rotation.

As already mentioned, the dipole emits electromagnetic energy at the expense of the rotation. In a nutshell, the rotational speed continuously decreases. Astronomers actually observe such a slowing down, which becomes no-



Remnant: A ring of matter that was ejected from a supernova surrounds the neutron star SGR 1900+14.

Photo: NASA/JPL-Caltech; graphic: MPI for Astrophysics – Michael Gabler

Expert on things extraterrestrial: Michael Gabler studies the properties of a special type of neutron star, known as a magnetar, at the Max Planck Institute for Astrophysics in Garching.

Photo: Axel Griesch

ticeable in the pulses; with magnetars, it typically amounts to around three milliseconds per year.

The slowing down can be plotted as a function of time. From such a "spin-period/spin-down rate diagram," the experts calculate the strength of the magnetic field directly. The rule is: the larger the decrease in the pulse frequency, the stronger the magnetic field. The researchers can thus quickly ascertain whether an observed pulsar is a magnetar. Gabler and his colleagues use primarily the data from the *Swift* gamma ray satellite and the *Rossi* X-ray satellite.

FIELD LINES TWIST LIKE RUBBER BANDS

The observations can also be used to derive the mass and the radius of the neutron star. The former is two solar masses at most and can be determined from simple laws of celestial mechanics if the star is a partner in a binary system. The radius escapes direct measurement – the astrophysicists have to derive its value indirectly, from the varying light intensity, for instance.

Once the scientists have a magnetar in their sights, further measurements over a longer period are worth the effort. A number of these celestial bodies sometimes exhibit giant flares, usually in the gamma and X-ray range. These indicate the catastrophic collapse and subsequent reorganization of the outer magnetic field, as the neutron star also has a second, inner magnetic field. Over time, this forces its configuration

» Deep in the heart of a neutron star, the density is three times that of an atomic nucleus, and the temperature is around one billion degrees.

onto the outer field, which is why the outer field lines twist more and more, like rubber bands.

"At some point, the stress is too great, and the lines suddenly break open and rearrange themselves. This reconnection generates the radiation that is measured," says Gabler. A sort of fireball of hot plasma is created and is trapped in the magnetic field. During the few tenths of a second that such a flare lasts, the star releases as much energy as our Sun in 1,000 years.

In some objects, the flares are followed by further, weaker bursts after hours or years. The strong magnetic field also plays a role in the case of such a soft gamma-ray repeater. It apparently has an effect on the crust of the neutron star, setting it in motion, maybe even breaking at one point or another.

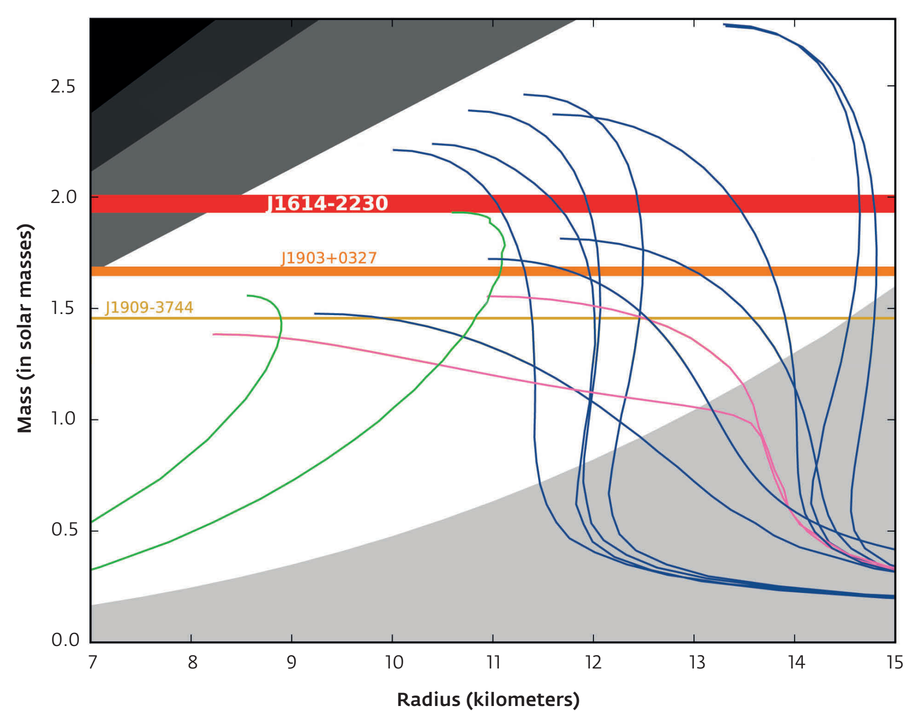
How do we know this? Each explosion changes the light from the object, meaning the astronomers observe a number of specific frequencies in its X-ray spectrum. According to theory, they originate from oscillations of the neutron star. In analogy with seismology, which investigates earthquake waves, or helioseismology, which studies oscillations on the Sun, it should be possible to use asteroseismology to analyze the structure of a neutron star. In fact, the task now is to construct, on the computer, a neutron star that delivers the observed frequencies. "The orders of magnitude of the frequencies match those of elastic shear oscillations of the stellar crust very well," says Gabler.

The astrophysicists also observe a further type, called Alfvén oscillations. This kind of magnetic wave occurs on the Sun, as well, where they apparently help to heat up the outer atmosphere (corona). In the case of neutron stars, the Alfvén oscillations aren't restricted to the crust, but also provide information on the liquid core. More on this later.

THE OSCILLATIONS SEEM TO INDICATE STARQUAKES

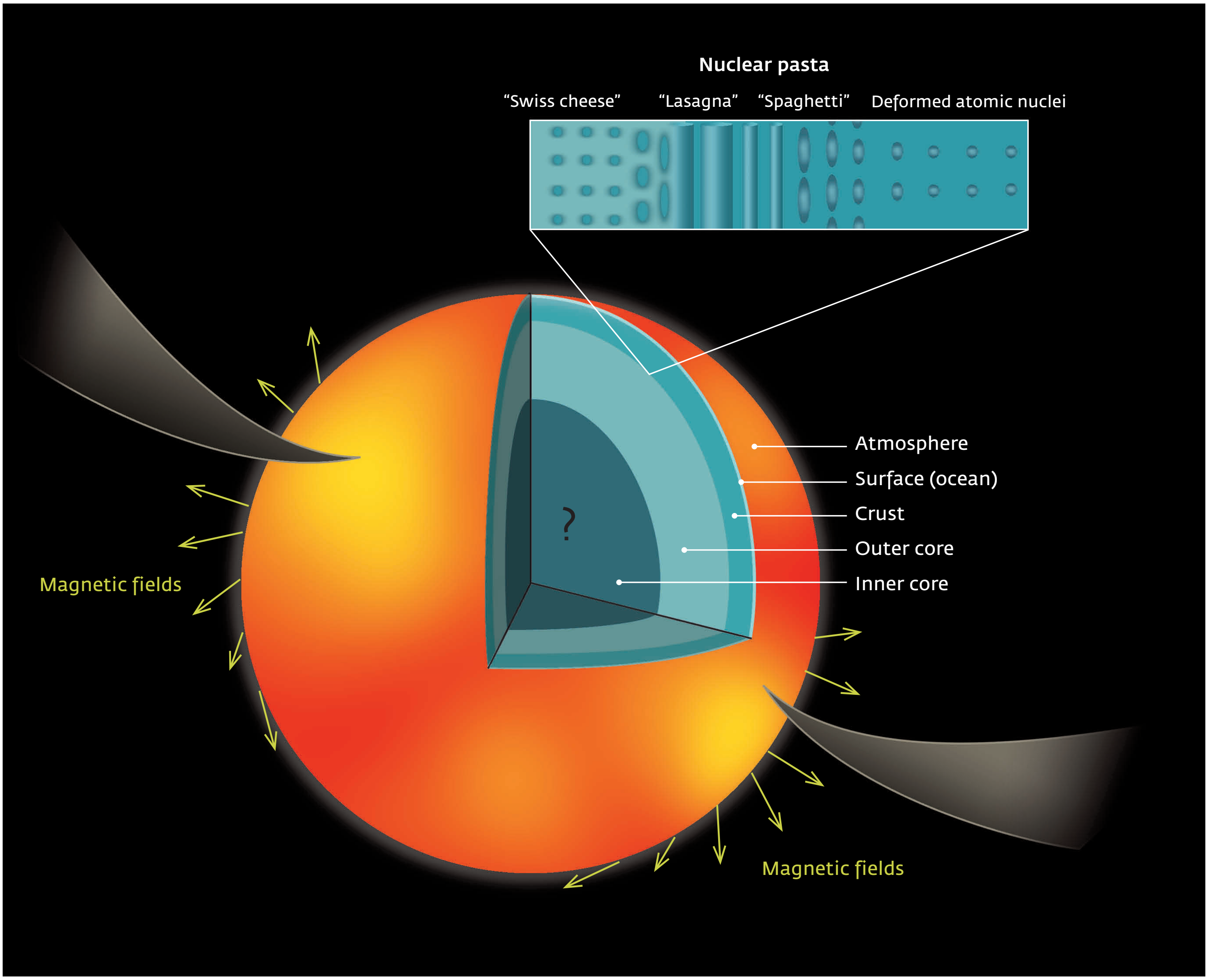
Michael Gabler and colleagues from other institutes have developed a model in which they couple the two aforementioned types of oscillations. Computer simulations show that the oscillations fit very well with the assumption of starquakes. Moreover, the strength of the coupling depends on the magnetic field: with weak magnetic fields, the shear oscillations in the crust dominate; with strong magnetic fields, it is the Alfvén waves in the core.

Core, crust, magnetic fields – so what exactly does the interior of a neutron star look like? According to the model accepted by most researchers, the density deep in the heart of a neutron star is three times that of an



The diagram shows the ratio of mass to radius for the neutron stars J1640-2230, J1903+0327 and J1909-3744. The curves represent different state equations, which provide corresponding masses for certain radii. Only when a curve crosses the bar of the neutron star in question – that is, reaches or exceeds its mass – can the corresponding state equation correctly describe the star. The colors of the curves indicate that different forms of matter were assumed in the state equations: blue stands for nucleons (protons and neutrons), magenta for nucleons plus exotic matter, and green for strange quark matter.

Graphic based on: Demorest et al., Nature, vol. 467, issue 7319 (2010)



Graphic: designergold, based on original material from Danny Page, Universidad Nacional Autónoma de México

Layered form: The structure of a neutron star resembles the skins of an onion. Deep in the interior, the matter can be described, at best, by the laws of quantum mechanics; it may be a mixture of free quarks and gluons. The outer core consists of 95 percent neutrons, while the remainder is protons and electrons. This is followed by "nuclear pasta," in which the atomic nuclei are elongated to a spaghetti-like form; further inside, these spaghetti look like the layers of lasagna, and yet further toward the core, the structure resembles Swiss cheese. The crust of the neutron star consists of an ordered crystal lattice, as can be found in terrestrial solids. It is thought that its surface is covered by an ocean of liquid matter only a few centimeters deep, and this, in turn, is covered by an even thinner atmosphere of hot plasma.

atomic nucleus, with a temperature of around one billion degrees. Under these conditions, the matter can be described, at best, by the laws of quantum mechanics; state and composition are largely unknown. This innermost core may consist of a mixture of free quarks and gluons, the fundamental building blocks of matter. A different idea puts such exotic particles as pions or kaons at the center; both of these are mesons, unstable particles each consisting of a quark-antiquark pair.

In the outer core, things become slightly clearer: "Neutrons and protons coexist there right next to each other," explains Michael Gabler. The neutrons form the bulk of the matter, making up around 95 percent, while protons and electrons make up the rest. The protons are superconducting, meaning they have zero electrical resistance.

Gabler's magneto-elastic model likewise provides an unusual state for the neutrons: they appear to be superfluid. Accordingly, they have no internal friction (no viscosity) and have an infinitely high thermal conductivity. In a terrestrial laboratory, superfluidity can be observed only at extremely low temperatures and for only a few elements; with helium, for example, it occurs at minus 270 degrees Celsius.

» The magnetic field is bound to the magnetar and rotates with it. A few thousand kilometers above the surface, it practically reaches the speed of light.

Experts use the term “nuclear pasta” to describe what is just outside the core. In the outer region of this zone, the atomic nuclei are elongated into the form of spaghetti. Further inward, these spaghetti form slabs, which are similar in structure to lasagna. Even further toward the core, the spaghetti is compressed under increasing pressure to form a uniform dough-like mass in which only very few cavities remain. “The whole thing resembles Swiss cheese,” says Gabler.

THE OCEAN ON THE SURFACE SLOSHES TO AND FRO

The overall crust is around one kilometer thick and consists of an ordered crystal lattice, as can be found in terrestrial solids. However, the atomic nuclei of the iron here are very rich in neutrons; for every 50 protons there are more than ten times as many neutrons. In deeper layers, the high pressure squeezes them out of the atomic nuclei and they can then move freely in the crystal lattice. Electrons also whizz around in the entire crust.

Toward open space, the outer layer is probably formed by a thin atmosphere of hot plasma a few micrometers thick. Below it, the experts suspect there is a thin ocean of liquid matter only a couple of centimeters thick. It consists of hydrogen or of all sorts of elements that the neutron star sucks in from an accompanying star, if it has one, and that collect on the surface. Solely the strong gravitational force holds the atmosphere and ocean in place. In the light of neutron stars, the astronomers have observed tiny oscillations that indicate that the ocean may slosh to and fro. However, the experts aren’t sure whether magnetars have an ocean at all.

On the other hand, every neutron star does have a magnetic field in which particles such as electrons and their positively charged antiparticles, the positrons, move. The magnetic field is bound to the star and rotates with it – the greater the distance, the faster the rotation. At a distance of a few thousand kilometers, the magnetic field practically reaches the speed of light. Beyond this so-called light cylinder radius, the magnetic field lines open up, and electrons and positrons can escape.

“But the external magnetic field not only rotates with the star – one of our models describes how it is coupled to the magnetic field in the star’s interior,” says Michael Gabler. His conclusion: “During starquakes, the external magnetic field oscillates, as well, giving rise to very strong electric currents in the magnetosphere.” The photons released during a gamma flare are scattered by the charge carriers of these currents – electrons and positrons. “This scattering can explain the observed frequencies in the hard X-rays,” says the Max Planck scientist.

This example in particular shows that the theory on the composition and structure of neutron stars can’t be all that wrong. Quite a few questions remain unanswered, though. Magnetars will continue to attract researchers like Michael Gabler in the future. ◂

TO THE POINT

- **Neutron stars are the inconceivably dense remnants of supernovas.**
- **With a diameter of a mere 20 kilometers, they rotate rapidly about their axes, emitting cones of radiation into space in the process, and thus become visible as pulsars.**
- **About 10 percent of all neutron stars have strong magnetic fields; these stars are therefore known as magnetars.**
- **Magnetars occasionally exhibit violent radiation outbursts that originate from the catastrophic collapse and reorganization of the outer magnetic field.**
- **The neutron stars oscillate during the explosions. These oscillations can be observed indirectly, and ultimately provide information on the structure and composition of the star.**

GLOSSARY

Binary system: It is thought that more than half of all the stars in the Milky Way exist in binary or multi-body systems. In a binary star system, for example, two stars orbit a common center of gravity. The masses of the two partners can be determined from the orbital data.

Dipole: Two spatially separate poles, each having a different polarity (+, –). They can be electric charges or magnetic poles of the same size. A simple example of a dipole and its field is a bar magnet.

Dynamo effect: The generation of a magnetic field in the interior of a celestial body (planet or star) through electromagnetic induction. This is caused by the interaction between the motion of a substance (convection) in electrically conductive matter and the rapid rotation.