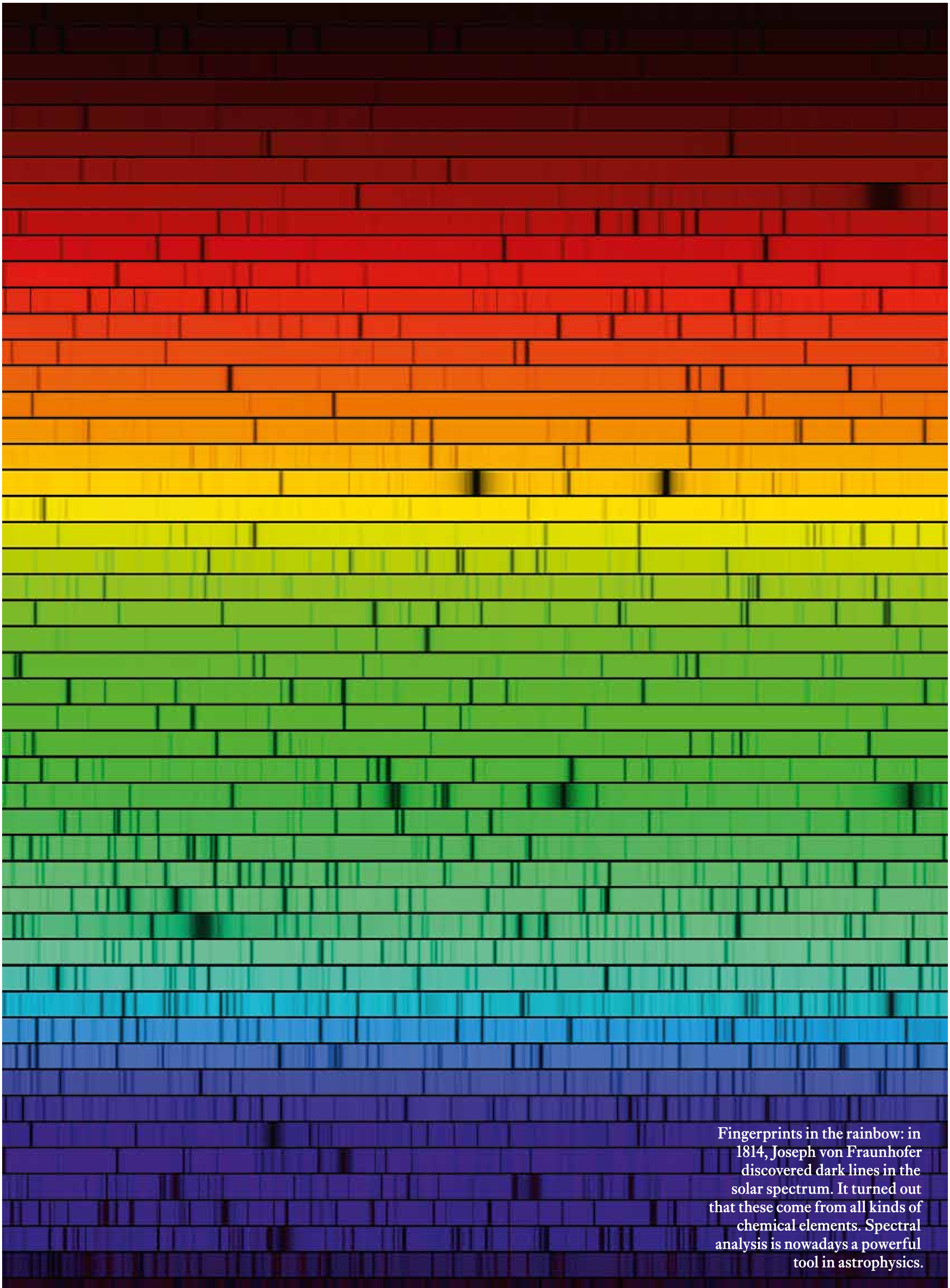

PHOTO: N.A. SHARP, NOAO/NSO/KITT PEAK FTS/AURA/NSF

Fingerprints in the rainbow: in 1814, Joseph von Fraunhofer discovered dark lines in the solar spectrum. It turned out that these come from all kinds of chemical elements. Spectral analysis is nowadays a powerful tool in astrophysics.

COSMIC DETECTIVE WORK

TEXT: THOMAS BÜHRKE

The chemistry of a star contains valuable information such as its history or affiliation with a particular stellar population. But accurate detection of abundances of chemical elements based on spectral fingerprints require highly sophisticated methods. Maria Bergemann from the Max Planck Institute for Astronomy in Heidelberg has set new standards here.

Nature is an elegant architect. From less than a hundred chemical elements, it has created a vastly diverse universe – from diffuse gas clouds to stars and from planets to intelligent life. The trick: atoms exert electrical forces, combine to form complex molecules, and can absorb and release energy.

The chemical composition of an object is decisive for its properties. For example, our Earth consists mainly of heavy elements such as iron, oxygen, silicon, and magnesium. On the other hand, the most abundant elements in space – hydrogen and helium – are also the lightest ones. Because of their volatility, they are relatively rare on Earth.

Stars like the Sun are hot balls of gas, and their surfaces typically reflect the chemical composition of the interstellar matter cloud from which they were born. "If we can assign each individual star in the Milky Way to a particular population in which it was born, we can reconstruct the entire history of this population, its genealogy," says Maria Bergemann, head of the Lise Meitner Group at the Max Planck Institute for Astronomy. The problem is that it is impossible to travel to the Sun – or to any other star – in order to take a sample of the gas in the stellar atmosphere. Researchers need a different method to determine the chemical composition of a star: stellar spectroscopy. These considerations are not new. But achieving this goal requires the state-of-the-art capabilities of telescope technology and the analysis of stellar spectra. For the latter, Maria Bergemann has followed in the footsteps of Joseph von Fraunhofer, Robert Bunsen, and Gustav Kirchhoff. In 1814, Fraunhofer used a glass prism to split sunlight into its rainbow colors. To his amazement, the resulting color fan contained about six hundred dark lines. Spurred on by this discovery, he also found dark lines in the spectra of very bright stars – sometimes at the same positions but with different widths and intensities compared to the lines in the solar spectrum. It is precisely these differences that provide information about the composition and nature of each star.

The decisive interpretation of the 'Fraunhofer lines' was achieved by Bunsen and Kirchhoff in 1860 in Heidelberg, where Maria Bergemann now carries out her research. During spectral experiments with gas burners, the scientists noticed that chemical elements within the spectrum produce a line at specific wavelengths. They were thus the first researchers to identify sodium in Fraunhofer's solar spectrum. Today, analysis of electromagnetic spectra is the most powerful tool in many areas of the natural sciences. This is especially true for astrophysics, as the vast majority of cosmic objects are inaccessible by any other means. The dark lines in the solar or in a stellar spectrum occur

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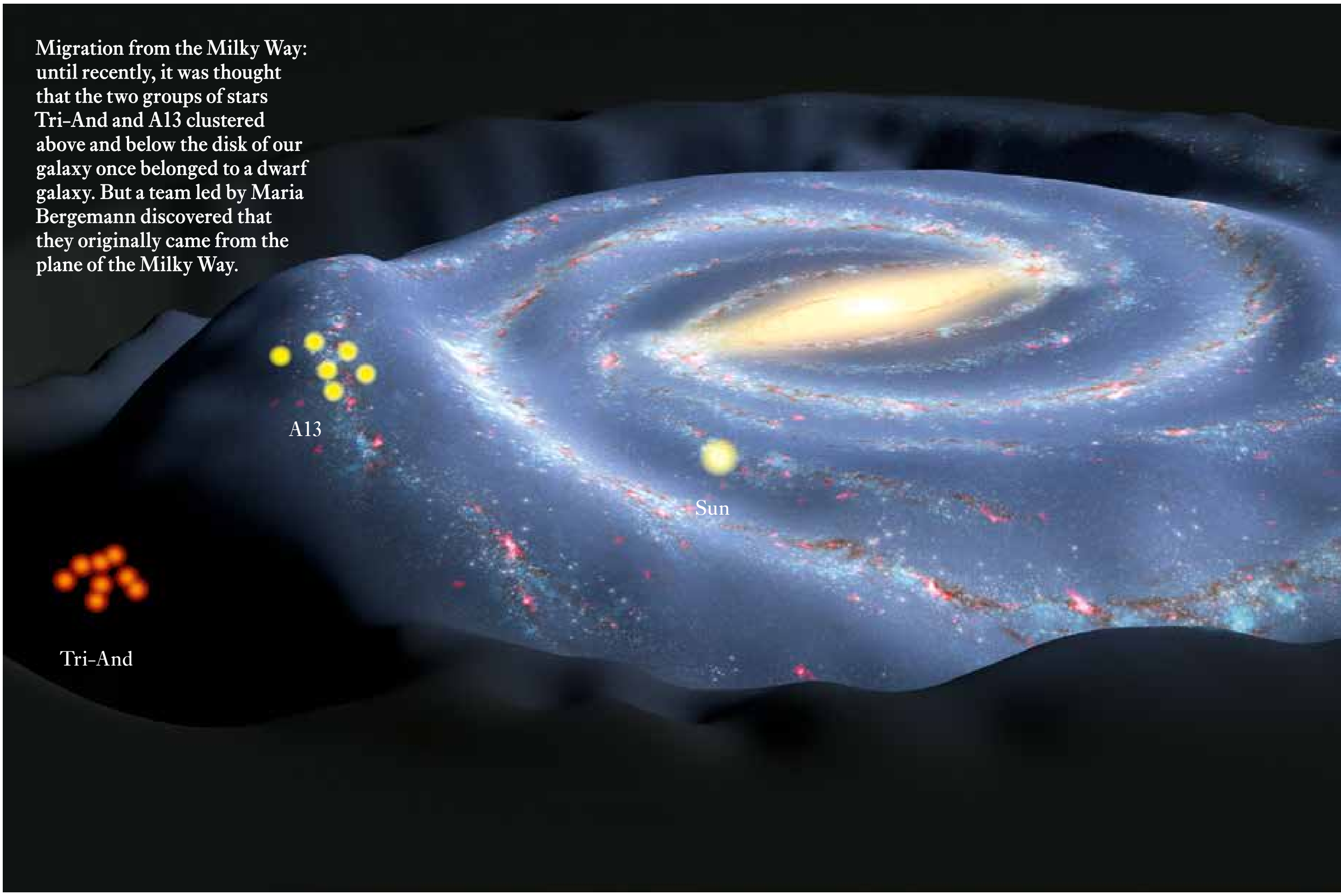

Migration from the Milky Way: until recently, it was thought that the two groups of stars Tri-And and A13 clustered above and below the disk of our galaxy once belonged to a dwarf galaxy. But a team led by Maria Bergemann discovered that they originally came from the plane of the Milky Way.

when light from the hot interior shines through the cooler outer atmosphere of the star. Atoms and simple molecules thereby absorb light at the wavelengths that are characteristic for them. A spectrum is much like a fingerprint. Several hundred thousand absorption lines are visible in the spectrum of the Sun. The critical question is: how can the element abundances be determined from the depth and width of the lines?

This requires atomic and molecular physical quantities that are measured in the laboratory. Current lists for modeling and interpreting solar spectra are based on more than one hundred million atomic and molecular lines. Many of them overlap and cannot be uniquely identified. This is one particular aspect that explains the complexity of spectral analysis.

Over the past hundred years, astrophysicists have developed theories and models in order to be able to calculate the physical parameters of stars using these spectral lines. These parameters include temperature, gas pressure, and gravitational acceleration at the surface as well as the detailed chemical composition. Such models are very complex and have to simplify reality. It was thus originally assumed that certain types of equilibria prevailed in a star. The balance of pressure and gravity leads to a hydrostatic equilibrium, while gas and radiation are in a so-called "local" thermodynamic equilibrium. "For decades, such highly simplified models were used to determine the abundances of chemical elements from spectra. But the results are sometimes wrong by a factor of five or more," says Maria Bergemann. A star is not a perfectly homogeneous sphere in which the same conditions exist at every point.

Most stars in the universe are about as heavy as the Sun or lighter. All of these star types have the same basic structure. In the outer region (which, in the case of the Sun extends to a depth of about 500,000 km), the gas is convective. Within that region – the convective envelope – masses of hot gas rise to the surface, cool down through emission of radiation, and sink back towards the interior. Water boiling in a pot shows a similar behavior. A pattern of well-defined cells emerges, and these can be observed as granules on the solar surface.

In addition to convection, various types of interactions between atoms and radiation occur in stellar atmospheres. Detailed models are therefore needed

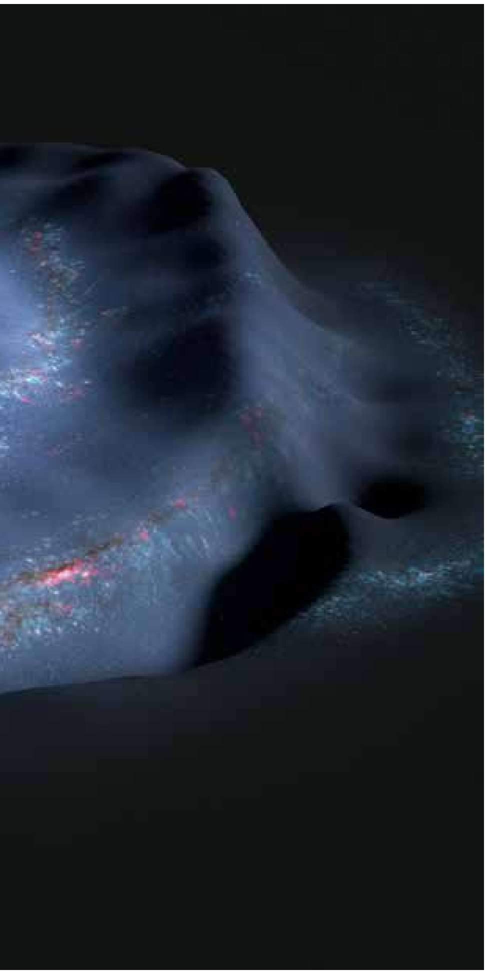

IMAGE: T. MUELLER/NASA/JPL-CALTECH

in order to calculate the chemical abundances from the measured spectral lines. For this, the paradigm of thermodynamic and hydrostatic equilibrium must be abandoned.

Models that do not rely on local thermodynamic equilibrium (non-LTE models) were developed as early as the 1970s. However, the practical application of these models in the analysis of stellar spectra became possible only about twenty years ago, with the development of powerful supercomputers. This has mainly to do with the countless excitation levels of atoms and molecules. For example, to represent the atom of a neutral iron, researchers must account for more than 600 energy levels, nearly 8,000 level radiative transitions, and 39,000 transitions caused by inelastic processes in collisions between iron and other atoms. In the beginning, the model atmospheres were one-dimensional. This was followed by a progression to two-dimensional calculations. Only recently it became possible to calculate non-LTE radiation transfer with three-dimensional convective models. However, clever and efficient algorithms are needed so that a computer can compute such models in a reasonable amount of time. Bergemann is considered a pioneer in this field.

But how do you find out which calculation gives the correct result? Here, the Sun acts as a benchmark. Each granule on its surface represents a convection cell with hot gas rising in its center and cooler gas sinking along the darker edges. However, the chemical composition does not change. Thus, if a spectrum is taken from the central region and one from the edge of the solar disk, the analysis must yield the same elemental abundances.

An analysis like this is possible only with the new, three-dimensional, non-LTE models. They correctly reproduce the shapes of the spectral lines that emerge from the hot and cooler regions. All calculations of different patches on the solar disk and different level transitions must result in the same self-consistent value. The three-dimensional non-LTE models can thus be reliably applied to other stars. "I spend about 95 percent of my time working on models," says Bergemann. She came to astronomy rather by chance. Born and raised in Kazan, Russia, she first worked in geophysics. But she soon realized that this subject just didn't interest her. "To be honest, I found it rather boring," she recalls. Her parents, who are themselves physicists, gave her the following advice: "If you want to discover some-

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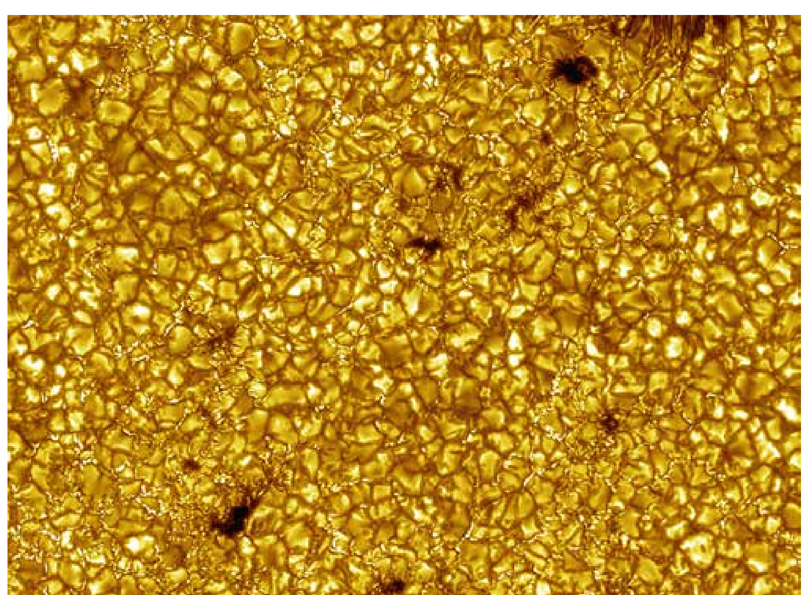

IMAGE: VASCO HENRIQUES

The Sun as a benchmark: many granules show up on the surface of our Sun. These convection cells, in which gas is constantly in motion, can be used to test models used for the spectral analysis of stars.

SUMMARY

The abundances of chemical elements in individual stars are like a fingerprint. They reveal the affiliation of a star to a stellar population.

The chemical differences of stars in the Milky Way or a distant galaxy can tell us a great deal about the formation and evolution of these stellar systems.

Calculating chemical abundances from a spectrum requires highly complex models as well as knowledge of properties of atoms and molecules, and of dynamic processes in stars.

thing fundamental, you have to go into astronomy." Intrigued, she followed this piece of advice.

She worked on stellar spectra as part of her diploma thesis at the University of Moscow. She turned down an offer of a doctoral position at Cornell University in favor of the Ludwig Maximilian University in Munich, where she received her doctorate in 2008. She then held Postdoc positions at the Max Planck Institute for Astrophysics in Garching and at the University of Cambridge before coming to the Max Planck Institute for Astronomy in Heidelberg in 2014. She now heads a Lise Meitner Group there.

Her analytical models are key to understanding vastly different astrophysical problems. It is not easy to pick out individual results from the many. But a recent event from the history of our Milky Way brought it to light. The Milky Way is a typical spiral galaxy in which most stars are associated to and move within the disk. But stars can also be found outside the disk – in the Galactic halo. Among others, there are two small groups of stars in the halo, each about 14,000 light-years above and below the plane of the Milky Way disk.

Until recently, most experts assumed that these groups – called Triangulum-Andromeda (Tri-And) and A13 – once belonged to a dwarf galaxy. But then an international team led by Bergemann obtained the spectra of these stars. The surprising result: the members of these two groups in the halo have an identical chemical composition that is indistinguishable from that of stars orbiting within the disk of the Milky Way.

The galaxy disk oscillates

"These stars most likely migrated out of the disk and are not remnants of a dwarf galaxy that collided with the Milky Way," says Bergemann about the result, which has since been confirmed by numerous other teams. Such stellar migration can be explained by an oscillation of the galactic disk, which is triggered by the tidal interaction with a massive satellite galaxy passing nearby. Computer models show that in this process, the outer disk of the Milky Way oscillated by as much as 30 degrees and so stars like those in Tri-And and A13 groups can be relocated from the midplane into the halo. The Heidelberg researcher and her team thus added another piece to the big puzzle of the evolution of the Milky Way galaxy.

Another result leads even further back into the past. In the Big Bang nucleosynthesis, the two lightest elements hydrogen and helium were created almost exclusively, with traces of lithium. The first stars fused these nuclei to heavier elements in their interiors. Via strong winds and during the explosions of massive suns as supernovae, the newly created elements entered the interstellar medium, where they were available to form the next generation of stars. These, in turn, incubated heavier elements in their interiors. Because of this cyclical process, the universe accumulated the heavy elements necessary for the formation of planets and life.

The first generation of stars probably formed sometime between 100 to 300 million years after the Big Bang. Whether any of them have survived to this day is unclear; so far, none have been proven to be that ancient. However, there are some stars in the Milky Way that contain so few heavy elements that they must have originated from one of the first generations. Bergemann's postdoctoral researcher Camilla Hansen selected two of these stars and calculated their chemical abundances. A comparison with nucleosynthesis predicted by supernova explosion models proves that these two stars belong to the second generation and consist of matter that was ejected by stars with 25 and 19 solar

Paradigm shift: does a type Ia supernova always result from the explosion of a white dwarf after it accreted enough matter from the companion to reach the critical mass(left)? Maria Bergemann's research group doesn't think so. Far more often, white dwarfs merge with one another after dancing around each other for a while (right).

masses, respectively. In this way, we can learn about the extinct first generation of stars.

Last year, Bergemann caused a bit of a stir in cosmology. She published a paper that targets one of the pillars of this science of the origin and evolution of the universe: dark energy. According to the present knowledge, dark energy is the dominant component of the universe and acts like an overpressure valve in a steam boiler. It inflates space and makes it expand at an accelerated rate. A spectacular discovery for which the American researchers Saul Perlmutter, Brian Schmidt, and Adam Riess were awarded the Nobel Prize in Physics in 2011.

The findings of the three scientists are based on their observations of a certain type of supernovae, which can be observed up to great distances and thus far into the past of the universe. It was once believed that most of these supernovae – of the so-called Type Ia – were caused by an ordinary star orbiting a white dwarf star. During this interaction, the white dwarf draws hydrogen from the outer layers of the companion and grows as a result. If it exceeds a certain mass, it explodes. Because this always occurs at the same mass, no matter how large the white dwarf was to begin with, all Type Ia supernovae are expected to be intrinsically equally bright and make excellent distance indicators. At least in theory. In reality, however, there are probably at least three other ways that a supernova Ia can form. For example, when two white dwarfs orbit each other, approach each other, and eventually collide. However, these types have distinctly different luminosities. This may affect the determination of the cosmic distance scale and the accelerated expansion calculated from that as well as the dark energy. How could we now find out which type of supernovae Ia predominates in space?

The different types of supernovae produce elements such as iron and manganese in different abundance ratios. And that's where Bergemann comes in. She and her colleagues determined the abundances of iron and manganese in 42 stars of varying ages. This allowed the team to reconstruct the history of manganese production in our galaxy. This led to an astonishing result. In order to explain the ratio of manganese to iron, three-quarters of all supernovae Ia in the Milky Way would have to be the result of merging

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IMAGE: NASA/SWIFT/AURORE SIMONNET, SONOMA STATE UNIV.

PHOTO: THOMAS HARTMANN

Against the mainstream: Maria Bergemann leads a Lise Meitner Group at the Max Planck Institute for Astronomy and has caused a number of paradigm shifts during the course of her research.

white dwarfs. This variety is therefore apparently the rule and not the exception as previously assumed. Could this have consequences for the theory of dark energy?

"I asked Adam Riess about that once," says Bergemann. "He wasn't thrilled about the idea. But he didn't elaborate on it." The new findings do not refute the concept of dark energy as a whole. However, they show that apparently some things are still unexplained in connection with this mysterious actor.

At any rate, Bergemann is looking forward to an exciting future. In 2020, she received the ERC Starting Grant worth nearly EUR 1.4 million for her "ELEMENTS" project. This will allow the industrious researcher to hire additional team members, who she needs for the 4MOST and WEAVE measurement programs. 4MOST – a project run by the European Southern Observatory (ESO) in Chile in which the Heidelberg Max Planck Institute plays a major role – will obtain high-quality spectra of more than 18 million stars in the southern sky. The WEAVE project on La Palma, in turn, will be recording millions of stellar spectra in the northern sky. Bergemann is now eagerly awaiting this treasure trove of data. But it all began with the discovery of the spectrum of the Sun more than 200 years ago.

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GLOSSARY

THE MILKY WAY
is a spiral galaxy with an estimated 200 to 300 billion stars. One of them is our Sun. The galaxy has the shape of a Frisbee, the edge of which arcs slightly. It measures about 100,000 light-years in diameter and is enveloped in a spherical halo.

SPECTRAL ANALYSIS
is a method that involves splitting the light emitted by an object into a "rainbow" by optical instruments. In the case of the Sun and other stars, characteristic lines appear in their respective spectra; these indicate certain chemical elements. This allows the chemical composition of these distant celestial objects to be studied.