Visible light makes up only a small part of the full spectrum of electromagnetic radiation. When lengths, they unmask strange landscapes and physical processes that remain concealed from astronomers use antennae or satellite-borne telescopes to look at the universe at those other wavelengths. A team of researchers led by Roland Diehl at the Max Planck Institute for Extraterrestrial Physics in Garching focuses on gamma-ray light, which has given them deep insights into the Milky Way – and even resorts to radioactivity as a source of these gamma rays.

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“My third observation concerns the nature of the Milky Way (...) No matter which part of it one targets with the telescope, one finds a huge number of stars, several of which are quite large and very striking; yet, the number of small stars is absolutely unfathomable.” The man who wrote this in March 1610 was using a self-constructed telescope to advance into unknown regions, for which he would go down in history: Galileo Galilei. He discovered what was literally out of this world – hence the book title “Sidereus Nuncius” (“The Starry Messenger”). In it, the Italian mathematician and astronomer described his observations of Jupiter’s satellites, the Earth’s moon and the Milky Way (box, page 23).

Examining this object, known as the galaxy, with the naked eye revealed the light of innumerable stars – suns similar to our own that generate their energy from the processes of nuclear fusion. The hot surfaces of these globes of gas radiate light like a burning candle. But stars are not the only bodies in the universe that generate thermal radiation. Astronomers are familiar with a variety of sources of thermal radiation: exploding stars (called supernovae), planets and even interstellar dust, which emits light at temperatures close to absolute zero, or minus 273.15 degrees Celsius.

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into the shortwave end of the thermal spectrum. But thermal processes can hardly generate any light at shorter wavelengths – nevertheless, the universe is full of such emissions. So where does this very high-energy gamma radiation originate?

**Exotic Means Beyond Hot**

It arises in exotic cosmic regions through "non-thermal" processes – non-thermal because the concept of temperature becomes devoid of all meaning here. Roland Diehl from the Max Planck Institute for Extra-terrestrial Physics in Garching thus describes these regions as "beyond hot." Researchers do not measure temperatures, but rather energies of radiation. What is more, these are not determined by temperature, but rather with a measurement of one millionth of a millimeter; and magnesium in sparklers fills the room with an almost white light. Astrophysicists identify such characteristic coloring as the fingerprint of the chemical elements. The closer one looks, the more clearly the spectral lines stand out. Incidentally, in the optical spectrum of the Sun or other stars, they appear as dark absorption lines, because the elements in the cooler stellar gaseous atmospheres absorb light that originates in the underlying interiors of the star at exactly those wavelengths at which they emit light by themselves.

**News from the Atomic Nucleus**

All these common features notwithstanding, there is a crucial difference between the optical and the gamma range: spectral lines in the visible part of the spectrum bear witness to processes inside the atomic nucleus, where unstable nuclei undergo spontaneous transformation. The modified nucleus then adopts a more stable configuration, thereby emitting gamma rays.

To distinguish between these source processes, researchers such as Roland Diehl do what researchers such as Friedrich Wilhelm Herschel, as a first step, did with sunlit objects 200 years ago: they split incoming radiation into a spectrum and sort it by wavelength. This results in a rainbow, the colors of which represent the different kinds of energy. "We use the color information in the spectrum to learn about the underlying processes," explains Diehl. This method might sound compli- cated, but its basics are familiar to everyone from us chemistry lessons at school: sprinkling sodium into the flame of a Bunsen burner turns the flame yellow and the spectrum exhibits an intense line at a wavelength of 589.2 nanometers (millions of a millimeter); and the area at the UV/IR end of the spectrum, bearing witness to thermal processes. This occurs when a charged particle, such as an electron, is diverted in the electric field of an atomic nucleus, converting part of its energy into radiation.

**Inverse Compton effect**

An effect: energy electrons transfer part of their energy to a particle of light, similar to a collision of billiard balls.

**Annihilation of matter and antimatter**

An electron finds its antiparticle, (positron) and both end up completely in gamma-ray light – in the form of two photons.

**Radioactive decay**

An element transforms into the atomic nucleus undergoes a spontaneous transformation. The modified nucleus then adopts a more stable configuration, thereby emitting gamma rays.

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**Bremstrahlung**

This occurs when a charged particle, such as an electron traveling at almost the speed of light, is diverted in the electric field of an atomic nucleus, converting part of its energy into radiation.

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A high-energy electron transfers part of its energy to a particle of light, similar to a collision of billiard balls.

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It arises in exotic cosmic regions through "nonthermal" processes - non-thermal because the concept of temperature becomes devoid of all meaning here. Roland Diehl from high-energy physics in particle accelerator laboratories, says Diehl. Rather than normal stars, flashes of subatomic particles, which represent the differential rotation with a galactocentric radius becomes constant, the Milky Way is filled with gas and dust clouds that absorb the light from the stars. This obscures the view, particular toward the galactic center, and prevents the overarching structure from being recognized.

Therefore, the stellar census will never be complete, except for the region around the Sun up to a radius of about 10,000 light-years. The breakthrough did not come until the middle of the 20th century, when astronomers had learned to look at the sky with different eyes: with radio telescopes. Hydrogen is the most common element in the universe. As part of interstellar matter, neutral hydrogen (H_I) fills the space between the stars, and fills the Milky Way. This means that the distribution of clouds of hydrogen gas trace the shape of the whole system, similar to the way in which bones shape the human body. But how can these "bones" be made visible? The nanouniverse provides the answer: in the ground state of hydrogen, the spin directions of the atomic nucleus and the electron that orbits around it are antiparallel. If two hydrogen atoms collide, the spin directions of the atomic nucleus and the electron may be flipped to end up parallel to each other - and then, after a certain time, they return to the antiparallel ground state.

This process releases energy which is radiated as an electromagnetic wave, its wavelength is 21.049 centimeters (frequency: 1420.4 MHz), and therefore lies in the radio range of the electromagnetic spectrum. Despite the extremely low density of interstellar matter, atoms will always collide frequently enough to cause events in atomic shells; lines in gamma-ray light, however, reflect processes inside the atomic nucleus. Furthermore, gamma radiation is very energetic with extremely small wavelengths - between one billionth and ten trillionths of a millimeter.

**A Fried Egg in the Universe**

In the early 17th century, Galileo Galilei discovered that the Milky Way consists of individual stars. Almost 150 years passed before a scientist again concerned himself with this celestial structure. Friedrich Wilhelm Herschel promised a solution: Her- schel recorded the coordi- nates and brightness of all stars visible through his telescope. The undertaking failed: apart from the uncertainty of these measure- ments - for example, it was possible to determine the apparent brightness of the stars, it was impossible to determine their absolute luminosity and hence their distance - there was also a fundamental problem: the Milky Way is filled with gas and dust clouds that absorb the light from the stars. This obscures the view, particularly toward the galactic center, and prevents the overarching structure from being recognized.

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However, in the 1970s, researchers found that hydrogen alone was not sufficient as an indicator for the galaxy's morphology because, for example, it is less concentrated in the spiral arms than expected. The search began anew.

The most important indicator turned out to be clouds of interstellar molecular hydrogen: they emit radiation in the characteristic light of carbon monoxide (CO) at a wavelength of 2.6 millimeters. Now it was gradually becoming possible to reflect the portrait of the Milky Way. Accordingly, the galaxy (from the Greek word gala: milk) is a slightly bent wheel, 100,000 light-years in diameter and 5,000 light-years in thickness. The central black hole is surrounded by a spherical huddle of stars with an embedded, elongated, cylindrical structure - a kind of bar – approximately 15,000 to 25,000 light-years in length.
The Cycle of the Element

The universe is like a chemist's laboratory; nature has created 83 chemical elements with a total of 284 atomic nucleus configurations (isotopes). The two most abundant elements, hydrogen and helium, originated from the Big Bang around 14 billion years ago, and still comprise approximately 58 percent of normal baryonic matter in the universe today. But back then, small quantities of lithium and beryllium were also created. As chemical evolution continued, fusion reactions in the interiors of stars then formed the heavier elements, up through iron.

In this way, massive stars use nuclear fusion to create the energy they need to prevent collapsing under the huge force of gravity until, finally, the interior of the star is composed of iron – the most stable element. Elements that are heavier than iron (such as silver, gold, lead and platinum) are created by the successive capture of neutrons. This process probably takes place in the interior of many kinds of stars, presumably also in supernovae explosions and in the form of energy of two neutron stars.

The nuclear reactor of a low mass star, such as the Sun, converts hydrogen to helium over billions of years. If the supply of fuel runs low, the end will come when the star will consist only of helium, the "ash" from hydrogen burning. At this stage, the globe of gas expands to become a Red Giant. In stars that are more massive than the Sun, hydrogen burning is followed by helium burning to produce carbon and oxygen. Stars in this late stage of evolution develop strong winds: light from the interior gives momentum to the gas cloud that exists over periods of 100 million years.

In other words, the astrophysicists measure radioactive energy wherever new atomic nuclei are produced in large quantities. Thus, astronomers, which also originates from the interiors of massive stars, is released in stellar explosions and leaves its fingerprints in the gamma radiation of supernova remnants, for example in the spectra of SN 1987 A or Cassiopeia A. This explains galactic radioactive matter well. Nucleosynthesis undoubtedly took place in massive stars billions of years ago, but it is still replenishing radiophotostopes today. Cassiopeia A, for example, exploded just 350 years ago in the Milky Way. When astrophysicists study the gamma-ray lines of isotopes such as $^{26}$Al, $^{44}$Co (cobalt) or $^{44}$Ti (titanium), they learn much about the cycle of elements in the cosmos (see box, left).

A Supernova as a Midwife?

But what does the birth of our solar system have to do with a supernova? Some scientists suspect that a cosmic catastrophe of this nature was literally the trigger for interstellar material to accumulate and form the primordial solar nebula. "Almost anthropocentric view," in Diehl's opinion, "then a very nearby source of nucleosynthesis would have been almost the trigger for interstellar material to accumulate and form the primordial solar nebula. Therefore, the next step is to look for these bursting stars. In other words, the astrophysicists measure radioactive energy wherever new atomic nuclei are produced in large quantities. Thus, astronomers, which also originates from the interiors of massive stars, is released in stellar explosions and leaves its fingerprints in the gamma radiation of supernova remnants, for example in the spectra of SN 1987 A or Cassiopeia A. This explains galactic radioactive matter well. Nucleosynthesis undoubtedly took place in massive stars billions of years ago, but it is still replenishing radiophotostopes today.

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for life on Earth – the Earth’s atmosphere is too thick for cosmic gamma rays. That is why high-energy physicists must resort to satellites in space – such as the European observatory Integral (INTeGral Gamma Ray Astrophysics Laboratory). Scientists used such observatories orbiting in space beyond the Earth’s atmosphere to discover a well-defined spectral line at 511 kilo-electron volts (keV) in the gamma-ray spectrum of the galaxy; exactly where the finger-print of the annihilation of electrons and positrons was expected to be ("The Dark Side of the Milky Way," page 40 ff.).

**Radioactivity**

**IMPLIES PRODUCTION**

But gamma-ray emission from the Milky Way reveals even more. In 1978, researchers found a line in the spectrum at 1808.65 keV. This is the energy physicists predicted for the aluminum isotope $^{26}$Al with a half-life of about 700,000 years. In the 1990s, researchers around Roland Diehl detected this relatively long-lived radioactivity over wide areas along the plane of the Milky Way. This was considered direct evidence that radioactivity is omnipresent in the universe, and that new atomic nuclei are being produced in large quantities in our galaxy more or less at the present time.

This finding by the Max Planck scientists was a surprise in the context of another discovery: Traces from the decay of the same aluminum isotope, $^{26}$Al, had been shown, as early as the end of the 1970s, to have existed in meteorite samples of the early solar system. This radioactive energy obviously contributed to melting matter in the embryonic solar system, and thus mediated the formation of rocks from which the planets formed around 4.5 billion years ago. So, on the one hand, there was the gamma-ray signal from $^{26}$Al from the galaxy, marking the creation of this isotope in the very recent past, cosmologically speaking; and on the other, there were indications of considerable quantities of $^{26}$Al that had played a role in forming the environment of the early solar system.

The isotope is apparently ubiquitous. “We believe that $^{26}$Al is largely a by-product of cosmic nucleosynthesis processes,” says Roland Diehl. In other words, the astrophysicists measure radioactivity wherever new atomic nuclei are produced in large quantities. Thus, aluminum, which also originates from the interiors of massive stars, is released in stellar explosions and leaves its fingerprints in the gamma radiation of supernova remnants, for example in the spectra of SN 1987 A or Cassiopeia A.

This explains galactic radioactivity rather well. Nucleosynthesis undoubtedly took place in massive stars billions of years ago, but it is still replenishing radioisotopes today. Cassiopeia A, for example, exploded just 350 years ago in the Milky Way. When astrophysicists today study the gamma-ray lines of isotopes such as $^{26}$Al, $^{56}$Co (cobalt) or $^{44}$Ti (titanium), they learn much about the cycle of elements in the cosmos (see box, left).

**A Supernova as a Midwife?**

But what does the birth of our solar system have to do with a supernova? Some scientists suspect that a cosmic catastrophe of this nature was literally the trigger for interstellar material to accumulate and form the primordial solar nebula. “An almost anthropocentric view,” in Diehl’s opinion, “then a very nearby source of nucleosynthesis would have been needed.” The extra bonus (for us, here) is that Planck researcher links this with specific questions: Could $^{26}$Al input from such special regions distort our gamma-ray view of the Milky Way as a whole? And: How much radioactivity does the galaxy contain in total?

Diehl and his colleagues are hoping that the answer will be found with a spectrometer called SPI on board the Integral satellite. This instrument was built by scientists led by Volker Schönfelder from the Max Planck Institute for Extraterrestrial Physics, together with French colleagues at the Centre d’Etude Spatiale des Rayonnements in Toulouse and several other European research groups.

SPI determines the energy of gamma rays with a new precision method. The germanium detectors in the instrument are cooled to 90 degrees Kelvin (minus 183 degrees Celsius), and at regular intervals, a sophisticated heating method repairs damage done to their delicate crystal structures by the heavy bombardment of cosmic radiation. In this way, the sensors maintain their spectral precision for years – and considering the time-consuming measurement procedure, this is crucial. Gamma-ray photons from $^{26}$Al decay rarely hit the instrument, typically at intervals of minutes, and many months pass before the astrophysicists have gathered the thousands of these gamma-ray photons required to create a useful spectrum. Roland Diehl and his colleagues recently presented its latest results in Nature. The scientists used SPI to search for variations in this gamma radiation along the Milky Way.

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Stars evolve more intensively and rapidly the more massive they are. Nuclear reactions in their cores produce increasing heavy elements. This ordered nucleosynthesis proceeds faster with subsequent stages, creating magnesium or aluminum, and then finally iron. Because the iron nucleus has the maximum nuclear binding energy, production of even heavier elements requires great amounts of energy. A dynamic environment is needed with occasionally high neutron density – conditions such as those that prevail in a supernova. According to theory, the r-process takes place seconds after the beginning of the explosion and forms the print of the annihilation of electrons and positrons was expected to be ("The Dark Side of the Milky Way," page 40 ff.).
The galaxy rotates around its center, not rigidly like a wheel, but at different speeds for different distances from the “hub,” so that the “neighborhoods” along the radius change with time. At the location of our Sun, the orbiting speed is about 220 kilometers per second. Looking from our point of observation toward the central regions of the galaxy, we see stars or gas clouds that move either toward or away from us. This is where the Doppler effect comes into play, which anyone watching a Formula 1 race on television experiences: when the race car speeds past the microphone, the sound of the engine changes from high to low. In the optical equivalent, light waves from a source are compressed (higher frequency) as they approach a stationary observer and stretched as they recede from the observer (lower frequency). As color depends on frequency and hence wavelength, the light seems to shift into blue in the first case and into red in the second.

The researchers did indeed find a shift of this kind in the color (energy) of the gamma-ray line from $^{26}$Al. This fits well with the assumption that the radioactive sources really are part of the inner regions of the galaxy, rather than being located in foreground regions; furthermore, they rotate at just the speeds that were found in other observations of the central regions of the Milky Way. Roland Diehl takes it one step further: “Because we are fairly familiar with the geometric structure of the galaxy, we can assign the intensity to the relevant distances of the sources, and thus estimate the total quantity of radioactive aluminum-26.”

The result is surprising: the astrophysicists in Garching found three solar masses of aluminum-26 in the Milky Way. “This isotope is extremely rare in the universe. For example, the initial quantity in the young Sun was just fifty parts per million of that of the stable isotope, which is aluminum-27,” explains Diehl.

**A Landscape behind Clouds of Gas**

Apparently there are very efficient $^{26}$Al factories in the Milky Way. Theorists have long suspected supernovae of being the main suppliers of this isotope. Diehl and his colleagues have concluded from their measurements that, every century, two massive stars must explode as supernovae within the Milky Way to ensure the supply of observed $^{26}$Al. The scientists therefore consider this to confirm not only theory, but also findings in other galaxies similar to our Milky Way, where astrophysicists have observed just such a rate of stellar explosions.

Gamma radiation opens up a view onto a landscape that lies concealed behind dense interstellar gas clouds in the optical window. In coming years, the researchers want to continue their measurements with Integral to make them more precise. Once it was the light of innumerable stars that excited mankind; today, researchers enthuse over the diffuse glow of radioactivity. “Each isotope contributes its own story,” says Roland Diehl. That of aluminum-26 is particularly illuminating, not only for understanding the interior of our galaxy, but also the early history of our solar system. Michael Blum

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The SFI gamma spectrometer has allowed scientists at the Max Planck Institute for Extraterrestrial Physics to measure the gamma-ray line from radioactive aluminum-26 at such high precision that, for the first time, they can derive conclusions about astrophysical processes based on variations of its shape.