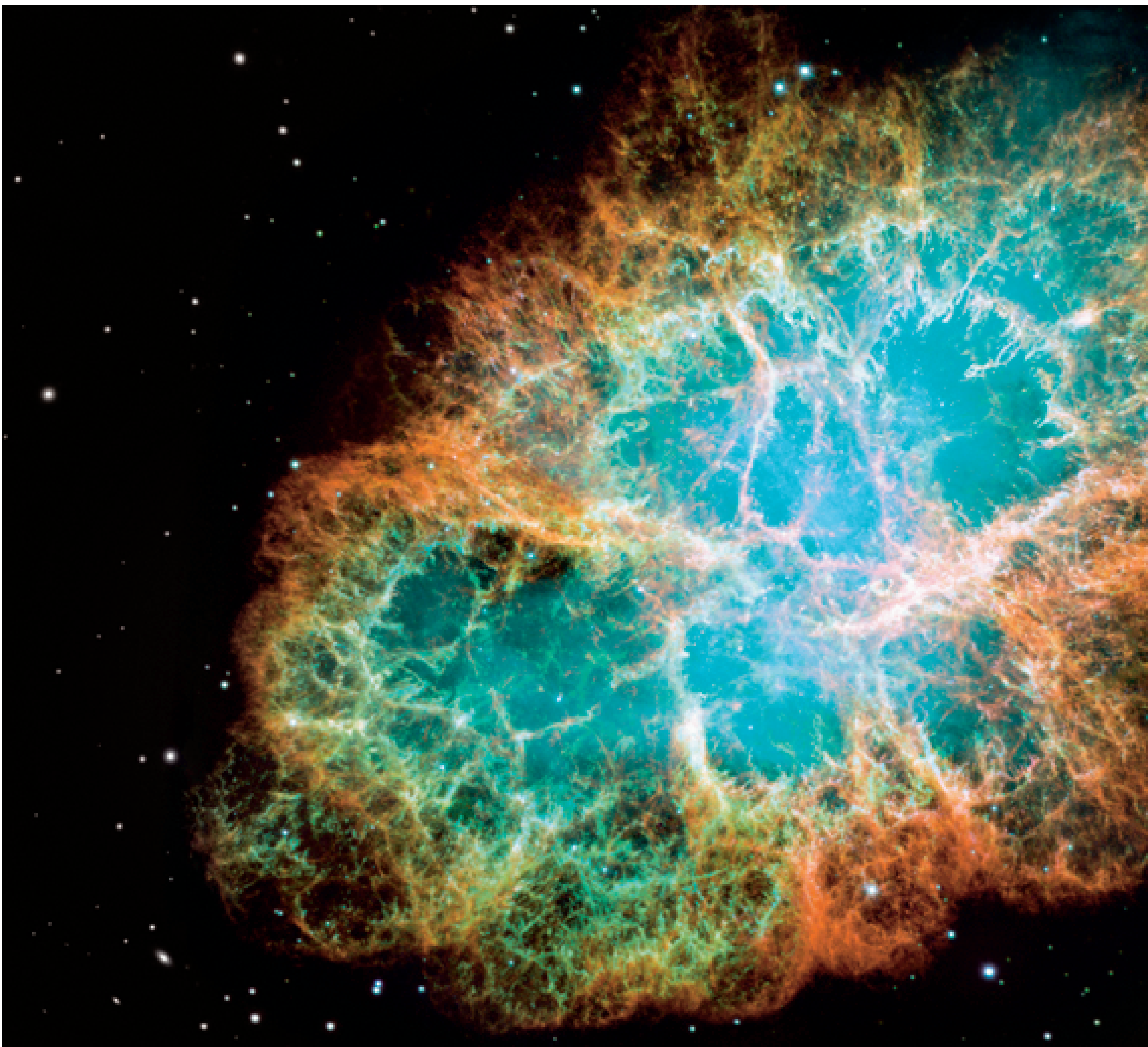
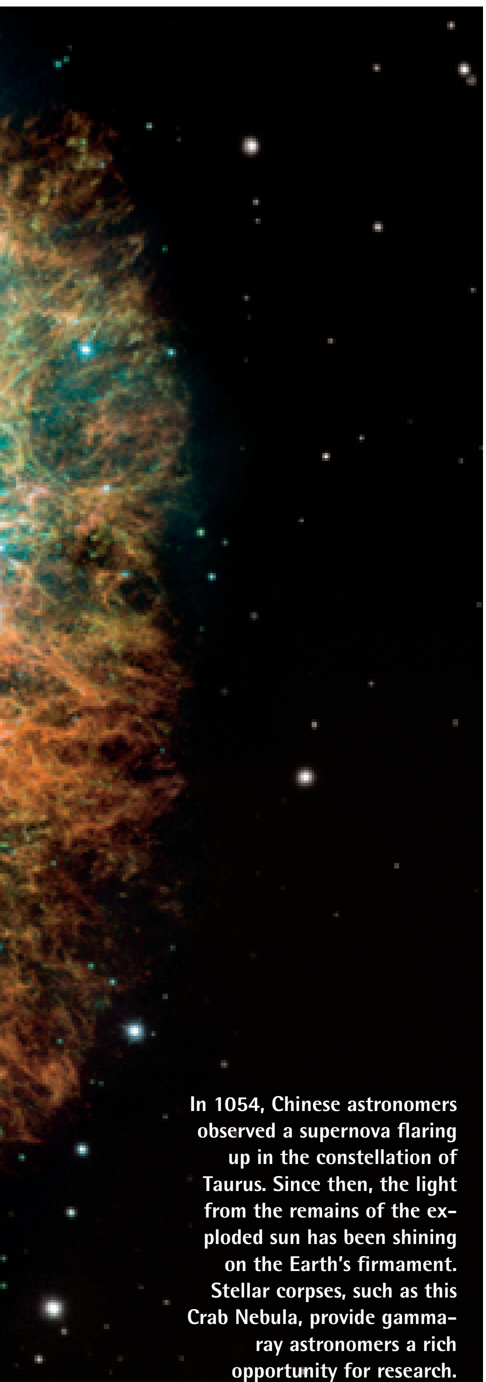
The Galaxy's

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 **Extraterrestrial Physics** *in Garching focuses on gamma-ray light, which has given them*



Gamma-Ray Glow

astronomers use antennae or satellite-borne telescopes to look at the universe at those other wave-
optical telescopes. A team of researchers led by **ROLAND DIEHL** *at the* **MAX PLANCK INSTITUTE FOR**
deep insights into the Milky Way – and even resorts to radioactivity as a source of these gamma rays.



In 1054, Chinese astronomers observed a supernova flaring up in the constellation of Taurus. Since then, the light from the remains of the exploded sun has been shining on the Earth's firmament. Stellar corpses, such as this Crab Nebula, provide gamma-ray astronomers a rich opportunity for research.

PHOTO: NASA/ESA/JEFF HESTER, ARIZONA STATE UNIVERSITY

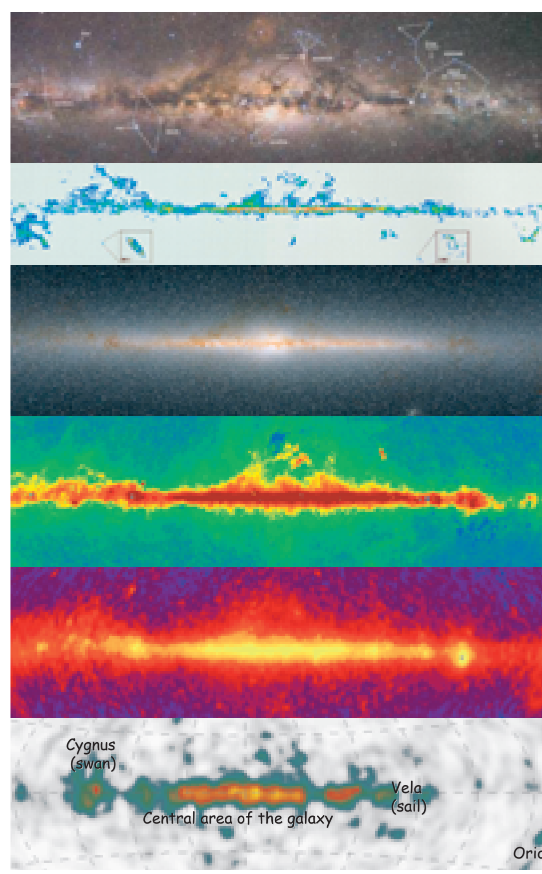
From time immemorial, human beings have looked up at the diffusely gleaming band of light that stretches across the sky on clear nights. For millennia, the mysterious glow remained largely a theme of mythology. In the 5th century BC, Greek philosopher Democritus expressed his belief that this "Milky Way" consisted of countless faint stars – a revolutionary claim at the time, and it was not actually confirmed until 2,000 years later.

"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).

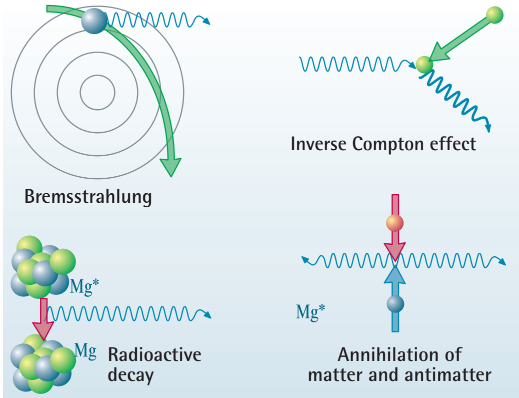
Examining this object, known as the galaxy, with the naked eye revealed the light of innumerable stars – suns similar to our own that generate their energy from the processes of nuclear fusion. The hot surfaces of these globes of gas radiate light like a burning candle. But stars are not the only bodies 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.

Whereas cold bodies emit infrared light at long wavelengths, hot supernovae emit a considerable part of their energy as X-rays, thus reaching

PHOTOS: MELLINGER/COLUMBIA UNIVERSITY/IPAC/MPI FOR RADIO ASTRONOMY/MPI FOR EXTRATERRESTRIAL PHYSICS



Our Milky Way as seen through various astronomical windows – that is, different spectral ranges: Visible light, radio emission from carbon monoxide, infrared light, the radio continuum range, gamma-ray continuum emission, and gamma rays with a specific energy that originates from radioactive decay (from top).



There are basically four different processes that produce cosmic gamma rays (description in the running text to the right).

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 Extraterrestrial Physics in Garching thus describes these regions as "beyond hot." Researchers do not measure temperatures, but rather energies of radiation, which can measure as much as 10^{20} electron volts – far more than can be generated by particle accelerators on Earth. "If we had gamma-ray eyes, we would see the Milky Way in the light of processes that are familiar to us from high-energy physics in particle accelerator laboratories," says Diehl. Rather than normal stars, flashes from pulsars and searingly bright interstellar gas would determine the overall picture of the galaxy, and this Milky Way band would show up prominently in the sky.

Astrophysicists distinguish between essentially four sources of cosmic gamma-ray quanta:

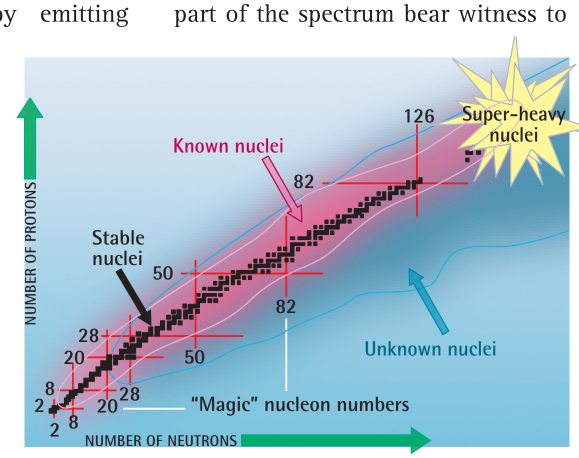
- **Bremsstrahlung.** This occurs when a charged particle, such as an electron traveling at almost the speed of light, is diverted in the electric field of an atomic nucleus, converting part of its energy into radiation.
- **Inverse Compton effect.** A high-energy electron transfers part of its energy 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 elementary constituent of the atomic nucleus undergoes a 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 Joseph von Fraunhofer first did with sunlight 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 complicated, but its basics are familiar to everyone of us from 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 (millionths of a millimeter); and magnesium in sparklers fills the room with an almost white light. Astrophysicists identify such characteristic coloring as the fingerprints of the chemical elements. The closer one looks, the more clearly the spectral lines stand out. Incidentally, in the optical spectra 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 would 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 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. Spectral lines are characterized by their energy, measured in electron volts, as stated above. Despite their penetrating power – and fortunately



Characteristic gamma rays provide access to the world of atomic nuclei – both in the universe and in particle accelerator laboratories on Earth.

Illustrations: Rohrer, based on originals from Roland Diehl, MPI for Extraterrestrial Physics

A Fried Egg in the Universe

In the early 17th century, Galileo Galilei discovered that the Milky Way consisted of individual stars. Almost 150 years passed before a scientist again concerned himself with this celestial structure. Thomas Wright of Durham believed that the stars were arranged as a flat object similar to a grindstone that stretched across the entire sky, and that the Milky Way was nothing but the projection of this grindstone.

German philosopher Immanuel Kant seized on this theory – and came very close to the truth. In his *General Natural History and Theory of the Heavens*, published in 1755, he explained the Milky Way as an extended and very diluted layer of stars. The Sun, the Earth and all the other planets were part of this layer, but not at its center. Depending on the line of sight, along the plane of the layer or vertically out of it, we would see different numbers of stars.

But how were the astronomers to find out whether the apparent view of the Milky Way in the sky reflected its actual spatial structure? Stellar statistics devised at the end of the 18th century by Friedrich Wilhelm Herschel promised a solution: Herschel recorded the coordinates and brightness of all stars visible through his telescope. The undertaking failed: apart from the uncertainty of these measurements – for example, although 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 central region, and prevents the overarching structure from being recognized.

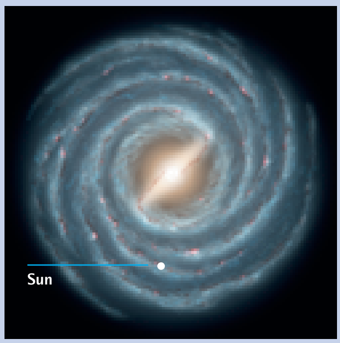


Illustration: Robert Hurt/SSC/Caltech/JPL/NASA

If we were to look at the galaxy from well outside of its plane, it would look like a Catherine wheel. Our sun is just one of about 150 billion stars.

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 (H1) fills the space between the stars, and thus 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 cosmic "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 nucleus and the electron may be flipped to end up parallel to each other – and 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 the H1 areas to glow in the light of the 21-centimeter-line. This radiation penetrates the dust curtains almost unobstructed and can be picked up by radio telescopes. The Doppler effect from the galactic rotation makes it possible to determine, from the measured wavelength, the distance of the source of radiation along the line of sight. This new window on the universe allowed astronomers to discover the spiral structure of the Milky Way.

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 molecules; 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 refine 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 center with its supermassive black hole is surrounded by a spherical bulge of stars with an embedded, elongated, cigar-shaped structure – a kind of bar – approximately 15,000 to 25,000 light-years in length.

A torus consisting mainly of dense dust and gas clouds with embedded stars surrounds the center at a distance of approximately 15,000 light-years. Several spiral arms make up the characteristic feature of the galaxy. Most of them bear the names of the heavenly constellations in which we observe them: the Sagittarius and Perseus Arms, the Norma and Scutum-Crux Arms, the 3-Kiloparsec Arms and the Cygnus Arm. Our solar system is located in the Orion Arm, 26,000 light-years from the galactic center and 50 light-years north of the main galactic plane. The system, which contains around 150 billion suns, is surrounded by a spherical halo containing thousands of globular star clusters and consisting of a thin hydrogen plasma.

The entire galaxy rotates; objects closer to the center rotate faster, and those further from the center, more slowly. The curve of this differential rotation with a galactocentric radius becomes constant at relatively small galactocentric distances; this cannot be explained by visible mass alone, and is the main argument for the existence of invisible dark matter.

And the astronomers face yet another problem: despite the rotation, the spiral arms do not unwind, but maintain their shape for billions of years. One explanation for this is shockwaves that compact the matter in the spiral arms and that propagate throughout the whole system like a traffic jam on the highway. Researchers are still puzzling over what causes these density waves.

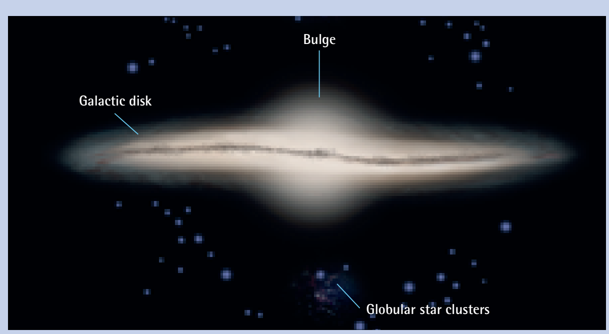


Illustration: Rohrer

From this perspective, the Milky Way looks like a fried egg in a pan – just 5,000 light-years thick at the center, flattening toward the outside, and 100,000 light-years in diameter.

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* (INTErnational 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 fingerprint of the annihilation of electrons and positrons was expected to be ("The Dark Side of the Milky Way," page 40 ff.).

Radioactivity Implies Productivity

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 con-

The Cycle of the Elements

The universe is like a chemist's laboratory: nature has created 83 stable chemical elements with a total of 284 atomic nucleus configurations (isotopes). The two most abundant elements, hydrogen and helium, originate from the Big Bang around 14 billion years ago, and still comprise approximately 98 percent of normal baryonic matter in the universe today; 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 supernova explosions and in the firework-like merging of two neutron stars.

The nuclear reactor of a low mass star, such as our Sun, converts hydrogen to helium over billions of years. If the supply of fuel runs low, the interior of 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, helium may ignite and burn to produce carbon and oxygen. Stars in this late stage of evolution develop strong winds: light from the interior becomes so intense that it overcomes gravity and carries the outer envelope away. After some time, only the more compact central part of the giant star remains, called a White Dwarf. In this way, chemical elements produced inside the star may escape and mix with the interstellar matter.

Stars evolve more intensely and rapidly the more massive they are. Nuclear reactions in their cores produce increasingly 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. Therefore, 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

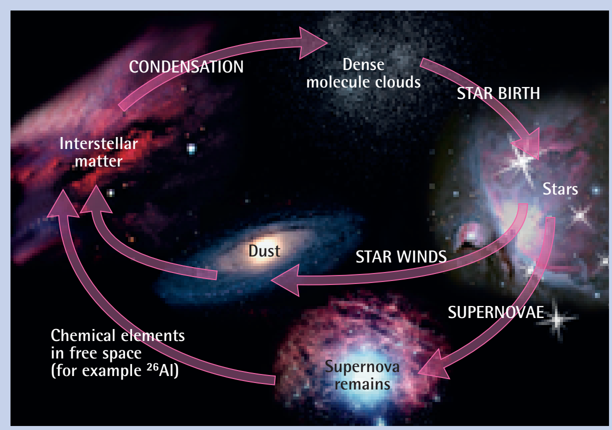
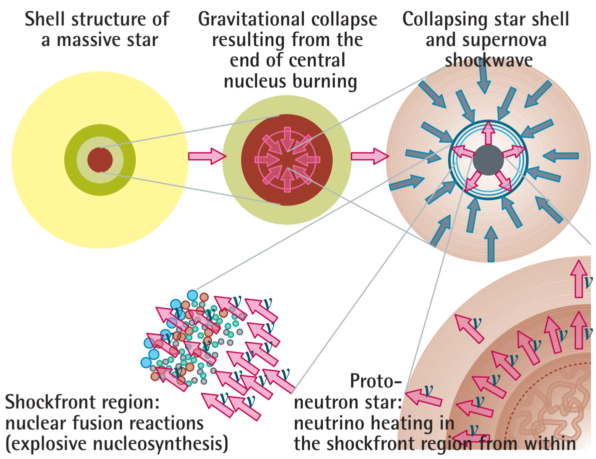


Illustration: Rohrer

Coming and going in the cosmos: This simplified illustration shows the cycle of the elements. Stars are born out of the interstellar matter, and after widely varying periods of evolution, return their "ashes" to the medium. Elements such as ^{26}Al drift about for only a relatively short time in the interstellar gas clouds that exist over periods of 100 million years.

elements such as germanium, lead or platinum as the iron nuclei successively capture neutrons. Astrophysicists consider the shockwave that travels through the exploding star at high speed and with great kinetic energy, pulling a kind of "explosive nuclear fusion flame" in its wake, to be another point at which elements are created.

Whether the cause is a more or less gentle stellar wind or a violent bang, the element-enriched debris from the star mixes with interstellar matter, which is how ^{26}Al is spread in space. The gamma rays from this isotope can be measured over millions of years – so there is much time available between release from their source and their radioactive decay. At some point, much later, the well-mixed gas composite fragments into dense interstellar clouds, from which spheres form, in which new fusion reactors light up, and the cycle is complete. The Sun belongs to one of the later star generations, formed from enriched gas. Our human bodies consist of atoms that were once inside stars: we are children of the cosmos.



Supernovae as retorts: When massive stars explode at the end of their lives, they create large quantities of elements heavier than hydrogen and helium. During such events, complicated processes take place in the interior of these bursting stars. When it's over, all that remains of these supernovae are compact neutron stars or exotic black holes.

ILLUSTRATION: ROHRER, BASED ON AN ORIGINAL FROM ROLAND DIEHL, MPI FOR EXTRATERRESTRIAL PHYSICS

text 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 hand, 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 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 primeval solar nebula; "an almost anthropocentric view," in Diehl's opinion, "then a very nearby source of nucleosynthesis would have been an extra bonus for us." The Max 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?

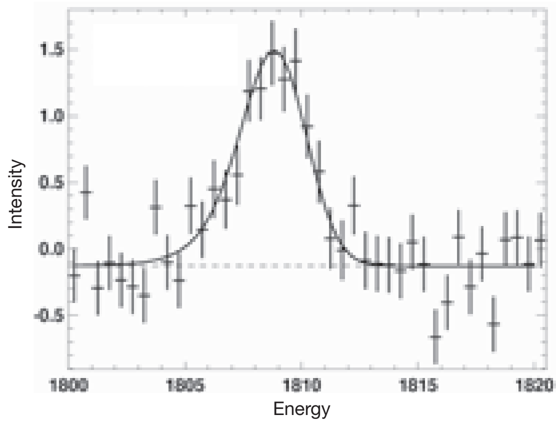
Diehl and his colleagues are hoping that the answer will be found with a spectrometer called SPI on board the *Integral* satellite. This instrument was built by scientists led by Volker Schönfelder from the Max Planck Institute for Extraterrestrial Physics, together with French colleagues at the Centre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

SPI determines the energy of gamma rays with a never before attained precision. 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's team recently presented its latest results in Nature. The scientists used SPI to search for variations in this gamma radiation along

PHOTOS: CESR

The SPI gamma spectrometer on the Integral satellite (top left). Unlike light, gamma rays cannot be bundled. An image is achieved by casting a shadow with the pattern of holes of a tungsten mask (top right). A type of camera made of 19 semiconductor detectors (bottom right) transforms gamma-ray interactions into voltage pulses.



The SPI 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.

the plane of the Milky Way and thus pinpoint their place of origin. To this end, they used a natural physical phenomenon and its consequences: the differential rotation of the Milky Way and the Doppler effect.

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.

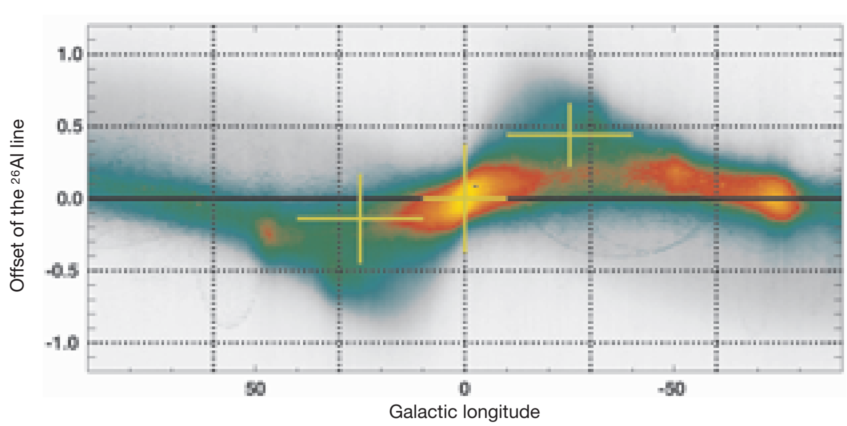
The researchers did indeed find a shift of this kind in the color (energy) of the gamma-ray line from ^{26}Al. This fits well with the assumption that the radioactive sources really are part of the inner regions of the galaxy, rather than being located in foreground regions; furthermore, they rotate 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. HELMUT HORNUNG



Through the Doppler effect, offsets in the aluminum-26 gamma-ray line energy provide insight into the inner regions of the galaxy. The illustration shows the energy of the gamma-ray line and thus the direction of motion in the central Milky Way, versus the viewing direction in units of galactic longitude. Regions to the right of the central region (0 degrees) are receding, while regions on the left are approaching the observer. In the first case, the researchers measure a lower, in the second a higher, energy value for the aluminum line.