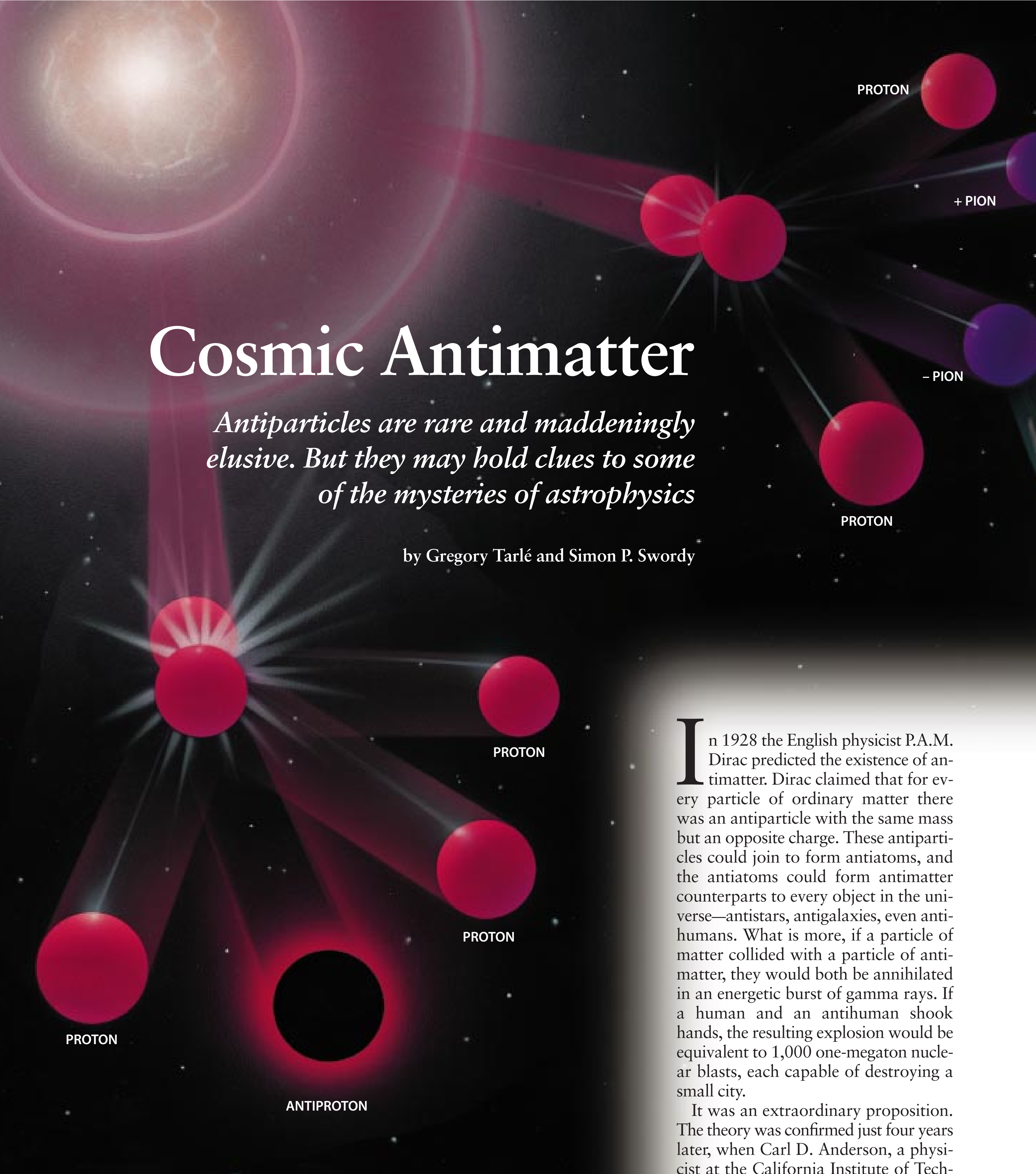
Cosmic Antimatter

Antiparticles are rare and maddeningly elusive. But they may hold clues to some of the mysteries of astrophysics

by Gregory Tarlé and Simon P. Swordy

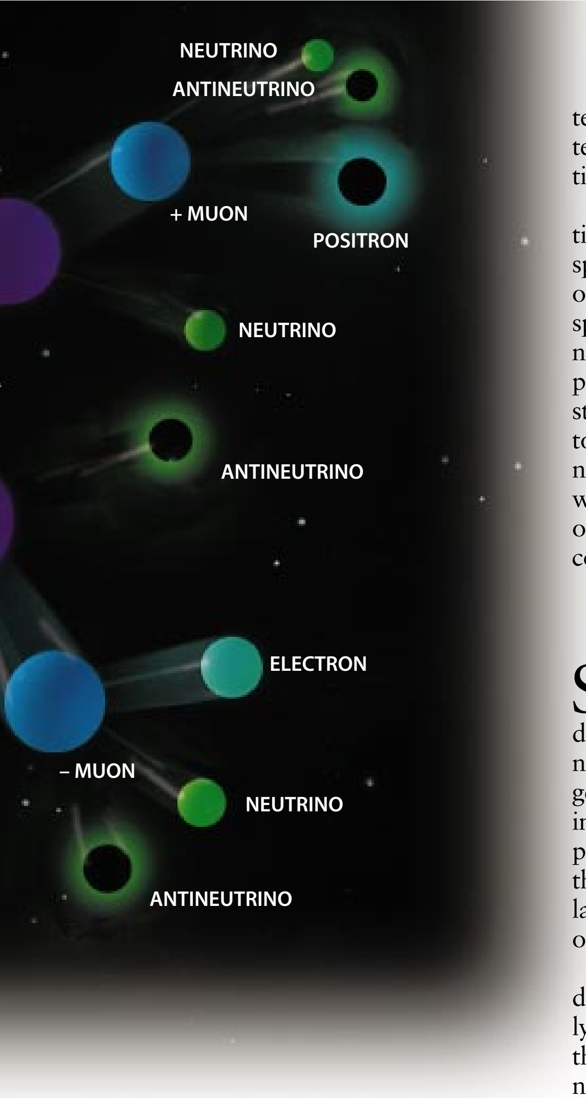


VIOLENT COLLISIONS of protons accelerated by a supernova shock front create much of the antimatter that scientists observe. Some collisions produce a shower of positrons, electrons and other particles (*top*), whereas the most powerful impacts generate antiprotons (*bottom*).

ALFRED T. KAMAJIAN

In 1928 the English physicist P.A.M. Dirac predicted the existence of antimatter. Dirac claimed that for every particle of ordinary matter there was an antiparticle with the same mass but an opposite charge. These antiparticles could join to form antiatoms, and the antiatoms could form antimatter counterparts to every object in the universe—antistars, antigalaxies, even antihumans. What is more, if a particle of matter collided with a particle of antimatter, they would both be annihilated in an energetic burst of gamma rays. If a human and an antihuman shook hands, the resulting explosion would be equivalent to 1,000 one-megaton nuclear blasts, each capable of destroying a small city.

It was an extraordinary proposition. The theory was confirmed just four years later, when Carl D. Anderson, a physicist at the California Institute of Technology, detected the first antiparticle. While using a cloud chamber to study cosmic rays—high-energy particles that bombard the earth from space—Anderson observed a vapor trail made by a particle with the same mass as an elec-



tron but an opposite (that is, positive) charge. Dubbed the positron, it was the antimatter counterpart of the electron. Antiprotons proved harder to find, but in 1955 physicists at Lawrence Berkeley Laboratory used a particle accelerator to create them. In 1995 scientists at CERN, the European laboratory for particle physics near Geneva, synthesized atoms of antihydrogen—for a brief instant—by merging positrons and antiprotons in a particle accelerator.

In recent years scientists have built sophisticated detectors to search for antimatter in cosmic rays. Because cosmic rays are destroyed by collisions with the nuclei of air molecules, researchers have lofted their detectors into the least dense reaches of the atmosphere. We are involved in one of those experiments, the High Energy Antimatter Telescope (HEAT), which rides on high-altitude balloons to detect positrons in cosmic rays. Other balloon-borne detectors can observe antiprotons. More ambitious antimatter searches on the drawing board include ones involving extended balloon flights and detectors orbiting in space. The results of these experiments could tell much about the origins of antimatter. They may also indicate whether antistars and antigalaxies really exist.

Astrophysicists believe most of the antiparticles observed in the upper atmosphere were created by violent collisions of subatomic particles in interstellar space. The process starts when the magnetic fields in the shock wave from a supernova explosion accelerate an interstellar proton or heavier atomic nucleus to enormous speeds. If this nucleus—now a high-energy cosmic ray—collides with another interstellar particle, part of the energy of the cosmic ray can be converted to a particle-antiparticle pair.

A Bucket of Cosmic Rays

Some collisions produce pairs of pions, unstable particles that quickly decay into positrons, electrons, neutrinos and antineutrinos. The most energetic collisions, involving particles moving at nearly the speed of light, produce proton-antiproton pairs. This process is the reverse of matter-antimatter annihilation: energy turns into matter instead of matter turning into energy.

Yet the number of antiparticles produced by interstellar collisions is relatively small. In the cosmic rays observed by the HEAT instrument, particles far outnumber antiparticles. To understand the difficulty of detecting antimatter, imagine a bucket filled with steel screws. A hundred of the screws have normal right-handed threads (representing the negatively charged electrons in cosmic rays), and 10 screws have left-handed threads (representing the positively charged positrons). Cosmic rays also contain protons, which are positively charged like positrons but far more massive. These protons could be represented by adding 10,000 heavier left-handed screws to the imaginary bucket. Now each left-handed screw must be weighed to see if it is a proton screw or a positron screw. And the weighing must be done very accurately. If only one in 1,000 proton screws is mistaken for a positron screw, the apparent number of positron screws will double.

The HEAT instrument has an error rate that is below one in 100,000. The device uses a superconducting magnet and an assembly of detectors to identify positrons. After cosmic rays speed through a collecting aperture, the superconducting magnet deflects the negatively charged electrons in one direction and the positively charged protons and positrons in the other. The detectors measure the charge and direction of each incoming particle, as well as the amount of deflection it experiences in the magnetic field. This last measurement helps to distinguish between protons and positrons; a proton, being heavier, will travel in a straighter path than will a positron with the same velocity.

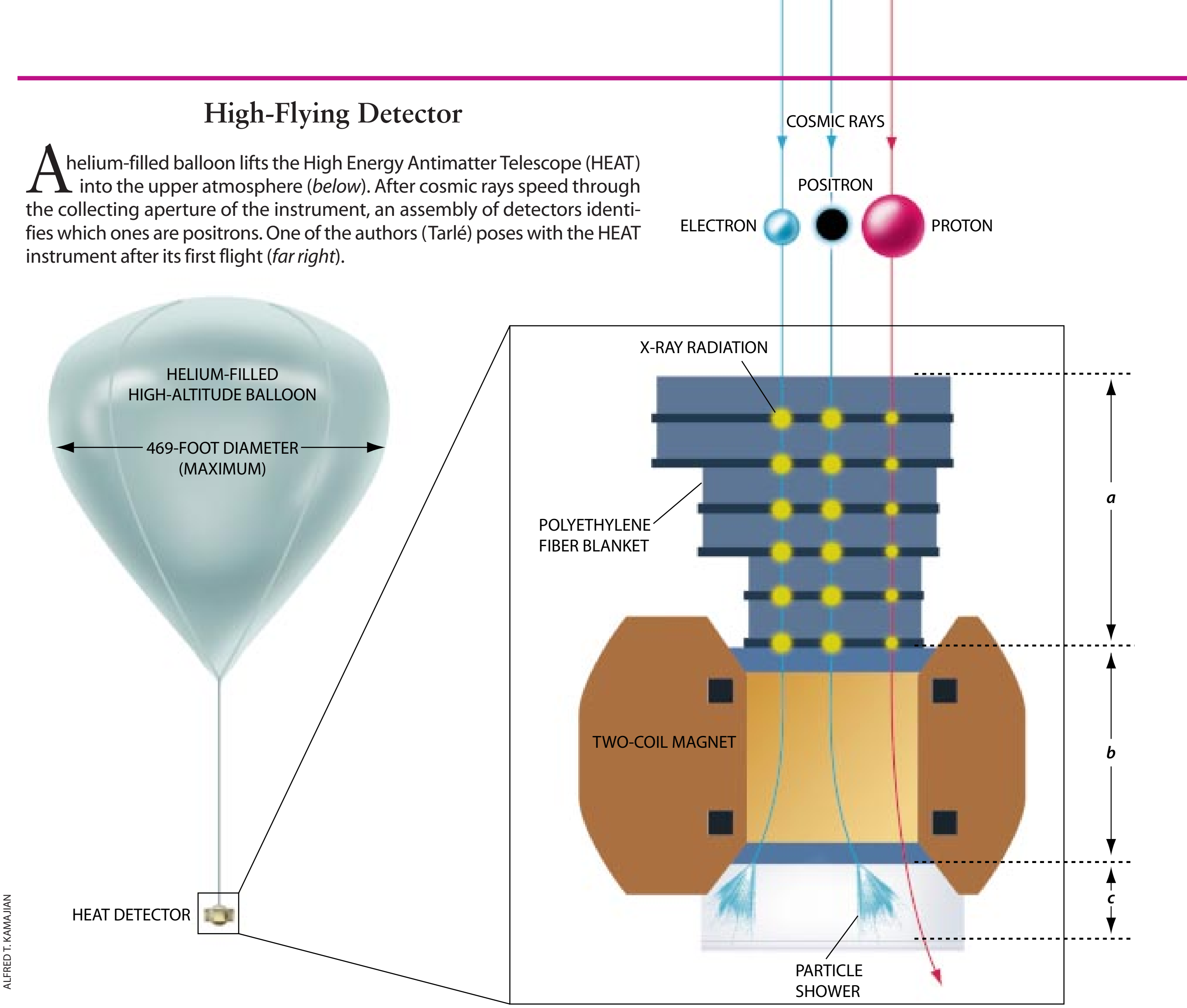
The National Aeronautics and Space Administration's scientific balloon facility launched the HEAT device for the first time in 1994 from a site in New Mexico. Although the device weighs about 2,300 kilograms (5,000 pounds), a giant helium-filled balloon raised it to an altitude of 37,000 meters (120,000 feet)—above 99.5 percent of the atmosphere. HEAT conducted measurements of cosmic rays for 32 hours, then parachuted to a soft landing in the Texas Panhandle. NASA launched HEAT again in 1995 from a site in Manitoba, Canada. The second flight allowed the device to observe lower-energy positrons, which can penetrate the magnetic field of the earth only near the north and south magnetic poles.

The results from these two flights were intriguing. The number of low-energy positrons recorded by HEAT was very close to the number expected to be produced by interstellar collisions. Yet the device found more positrons than anticipated in the high-energy range. The observed excess is not particularly large and could be the result of subtle errors. If the surplus is real, however, it suggests that an unappreciated source of high-energy positrons exists in the cosmos. One candidate is the putative weakly interacting massive particle, or WIMP.

This hypothetical particle offers a possible solution to the bedeviling "dark matter" problem. In order to explain the observed rates of galactic rotation, astrophysicists believe that each galaxy is embedded in a huge halo of dark matter that cannot be observed by ordinary means. The hypothetical WIMP would be a good candidate for the dark matter because it does not give off light or any other form of electromagnetic radiation. If WIMPs exist at the predicted density, collisions among them would produce a significant number of high-energy positrons. This process could account for the excess observed by the HEAT device. But before we and the other investigators involved can make that claim, future measurements from HEAT or other detectors must confirm our observations with greater precision.

High-Flying Detector

A helium-filled balloon lifts the High Energy Antimatter Telescope (HEAT) into the upper atmosphere (*below*). After cosmic rays speed through the collecting aperture of the instrument, an assembly of detectors identifies which ones are positrons. One of the authors (Tarlé) poses with the HEAT instrument after its first flight (*far right*).



ALFRED T. KAMAJIAN

While we have been hunting for positrons in cosmic rays, other scientists have been chasing an even more elusive quarry—the antiproton. Antiprotons are rarer than positrons because they are nearly 2,000 times heavier. Consequently, a much greater amount of energy is needed to create them. Interstellar protons must collide at speeds above 99 percent of the speed of light to produce a proton-antiproton pair.

Antimatter detectors such as the Isotope Matter Antimatter Experiment (called IMAX for short) and the Balloon-borne Experiment with Superconducting Solenoidal Spectrometer (dubbed BESS) have found a maximum abundance of only one antiproton for every 10,000 protons in the rain of cosmic rays. The rarity of these antiparticles forces the scientists searching for antiprotons to take special care to avoid false readings. Their detectors must have an error rate below one in a million to be sufficiently sensitive.

In Search of Antiworlds

The first extensive search for larger fragments of cosmic antimatter was the one initiated by the physicist Luis W. Alvarez in the 1960s. Alvarez began looking for heavy antiparticles, such as the nuclei of antihelium or anticarbon or antioxygen, in cosmic rays. Unlike positrons and antiprotons, these heavy antiparticles are too massive to have resulted from interstellar particle collisions. So the discovery of an antihelium nucleus would prove that some antimatter survived the big bang. And the detection of an anticarbon or antioxygen nucleus would reveal the existence of antistars, because carbon and all heavier elements are created only in stars.

Most astrophysicists are skeptical of the existence of antistars. Although light from an antistar would look the same as light from an ordinary star, the antistar would inevitably collide with particles of ordinary matter streaming toward it from interstellar space. The ensuing matter-antimatter annihilation would then produce a huge flux of gamma rays. Orbital detectors have observed low-energy gamma rays indicating the annihilation of an immense plume of positrons apparently extending from the center of our galaxy. Still, scientists do not believe these positrons are being produced by an antistar, which would appear as an intense, localized source of much more energetic gamma rays. The fact that no detector has observed such a source suggests that there are no antistars in the galaxy and, by similar reasoning, no

GEORGIA DeNOLFO

Section *a* shows the transition radiation detector, a series of six polyethylene fiber blankets. Positrons and electrons generate x-rays as they pass through the blankets, while protons of the same energy produce a much weaker signal.

Section *b* shows the magnetic spectrometer, which uses a superconducting magnet to deflect the cosmic rays. Electrons veer in one direction, while protons and positrons swerve the opposite way. Protons and positrons can be distinguished because a positron will curve more than a proton having the same velocity.

Section *c* shows the electromagnetic calorimeter, a stack of plastic slabs and thin layers of lead. When electrons and positrons hit the lead layers, they produce particle showers, which generate flashes of light in the plastic slabs. Most protons pass right through.

antigalaxies in the local galactic cluster.

What about farther away? Perhaps the universe contains isolated antigalaxies, separated by vast distances from galaxies of ordinary matter. In the past decade, astronomers have made extensive surveys of the distribution of galaxies as far away as a billion light-years. The surveys show no isolated regions that could conceivably be made of antimatter. Instead they show a web of galactic clusters surrounding great empty spaces, like a tremendous foamy bubble bath. If large parts of the universe were made of antimatter, the regions where matter and antimatter overlapped would have produced enormous amounts of gamma rays in the early history of the universe. Astronomers have not detected such a powerful background glow. Antigalaxies, if they exist at all, must lie beyond the range of our best telescopes—or at least several billion light-years away.

What is more, modern cosmology provides a reason why the universe can be composed almost entirely of ordinary matter. According to the most widely accepted theories, the big bang produced a small excess of matter over antimatter in the first instant of creation. This phenomenon occurred because of a slight asymmetry in the laws of physics, known as the CP violation, which has been observed in the laboratory. For every 30 billion particles of antimatter created during the big bang, 30 billion and one particles of matter also emerged. About a millionth of a second after the big bang, the particles began annihilating the antiparticles until only the excess ordinary matter was left. This small surplus—still a vast number of particles—became the universe as we know it.

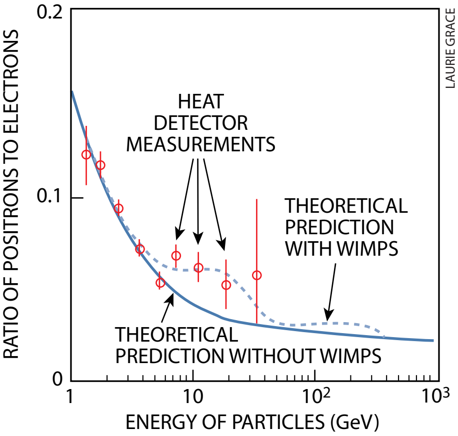
Although this theory seems persuasive, some scientists have continued searching for heavy antiparticles. They remain convinced that large regions of antimatter exist and that heavy antimatter nuclei moving nearly as fast as the speed of light could cross the huge expanse separating them from our galaxy. In the 1960s and 1970s Alvarez and other scientists deployed detectors that analyzed tens of thousands of cosmic-ray hits to determine whether any were made by heavy antiparticles. More recent experiments have sampled millions of cosmic rays. Despite all these efforts, no antiparticle heavier than an antiproton has ever appeared.

It is conceivable that distant antigalaxies are emitting heavy antiparticles, but the magnetic fields in intergalactic space prevent them from reaching the earth. Recent measurements of synchrotron radiation passing through galactic clusters have shown that the magnetic field within such clusters is about one millionth as strong as on the surface of the earth. Because such fields probably intensified 1,000-fold during the formation of the clusters, astrophysicists infer that the field between widely separated galaxies is only a billionth the strength of the field on the earth.

Although such a field would be too weak to nudge a compass needle, over time it would have a significant effect on an antiparticle traveling the enormous distances of intergalactic space. The path of the antiparticle would be bent into a helix, only a few light-years in diameter, around one of the magnetic-field lines. Astrophysicists do not agree on the orientation of magnetic fields in intergalactic space; some believe the fields are coherent, like the field around an ordinary bar magnet. Others claim the field lines are hopelessly tangled. If that is true, antiparticles could not travel far in one direction. They would bounce randomly amid the snarl of field lines. One can liken this movement to a drunken man trying to walk from a bar to his house 10 kilometers away. A sober man would walk in a straight line and reach his home in a few hours. But the drunkard takes steps in random directions and so makes little progress. He would be unlikely to reach his house even in a year.

If, on the other hand, the intergalactic magnetic field is coherent, the field lines could conceivably stretch from one galaxy to another. Under these conditions, antiparticles would be funneled between neighboring galaxies along cosmic highways that are millions of light-years long. The antiparticles still would not travel in a straight line; they would hop from one galaxy to another. It is as though our drunken wanderer is guided from one street corner to the next but still makes little progress because he moves randomly at the intersections. The antiparticles could travel only a few hundred million light-years from their starting point, even if they were given the entire age of the universe to make the trip. That distance is far shorter than the billions of light-years to the nearest possible antigalaxy.

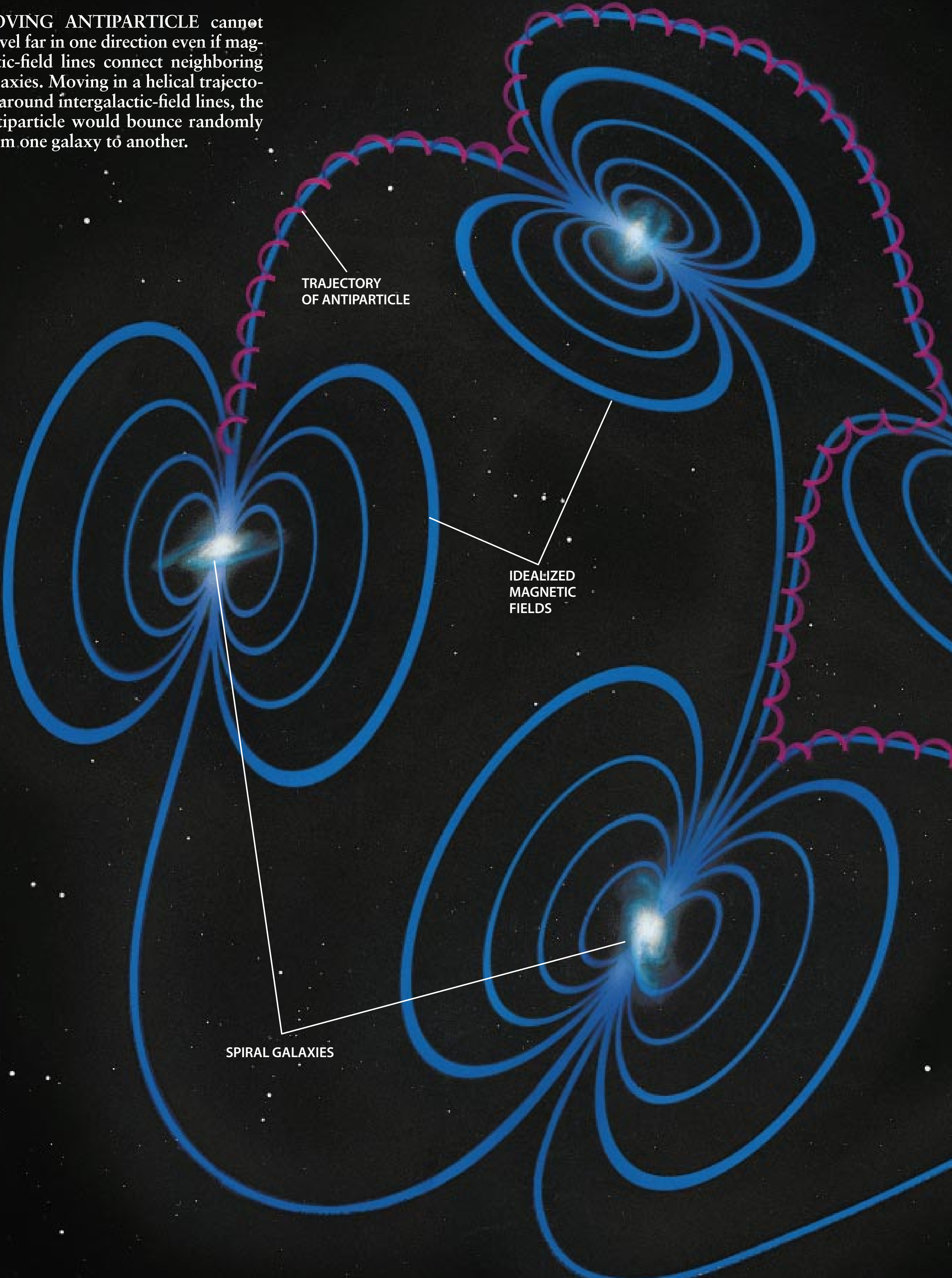
Even if, by some miracle of persistence, an antiparticle approaches our galaxy, it still may not reach the earth. Because the magnetic field inside the galaxy is far stronger than the field outside, it

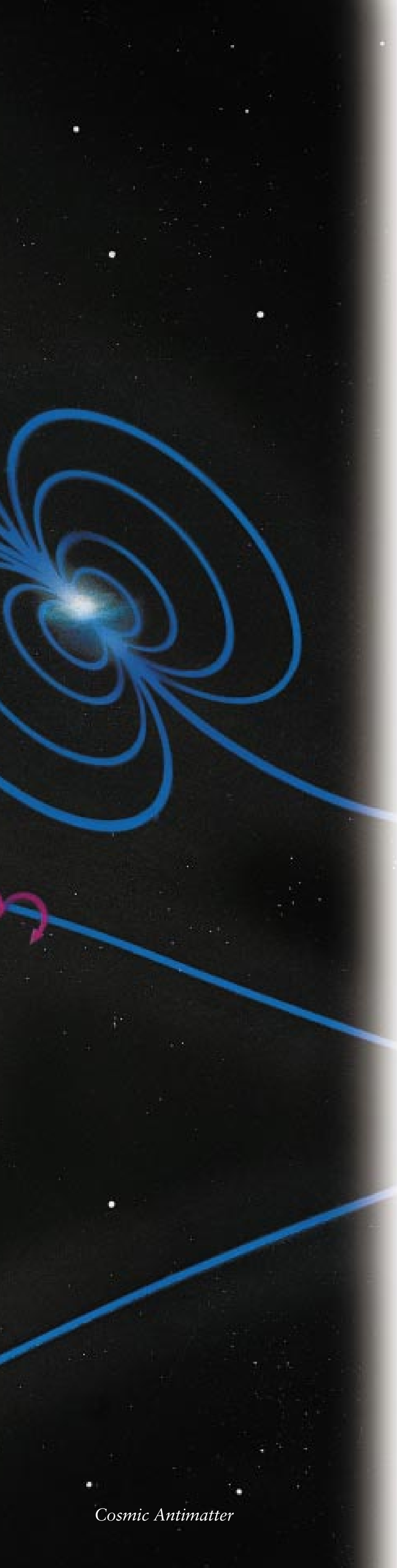


LAURIE GRACE

SMALL EXCESS in the number of high-energy positrons observed by the HEAT device may suggest another possible source of antimatter—the hypothetical weakly interacting massive particle, or WIMP.

ROVING ANTIPARTICLE cannot travel far in one direction even if magnetic-field lines connect neighboring galaxies. Moving in a helical trajectory around intergalactic-field lines, the antiparticle would bounce randomly from one galaxy to another.





ALFRED T. KAMAJIAN

will deflect the vast majority of antiparticles heading inward. The drunken man has finally made it to his house—and now he cannot find the key to the door.

Future Flights

It seems highly unlikely that heavy antiparticles will ever be found in our own galaxy. Nevertheless, the search continues. The U.S. Department of Energy is sponsoring a project to put an antimatter detector into orbit. The device, called the Alpha Magnetic Spectrometer (AMS), is primarily aimed at searching for heavy antimatter nuclei. NASA plans to test the AMS on the space shuttle later this year. If all goes as planned, the AMS will fly on the International Space Station for three years beginning in early 2002.

With such a long exposure time, the AMS would, in principle, have 100 times the sensitivity of previous antimatter detectors. The real challenge will be to ensure a commensurate level of accuracy in distinguishing between particles and antiparticles. To identify one heavy antiparticle from a background of 100 million particles, the detector must correctly determine the deflection of each particle in a magnetic field. The most precise balloon-borne instruments make 15 or more measurements to determine the deflection of speeding particles. The AMS will make only six.

Another device intended to observe cosmic antimatter from orbit, PAMELA, is scheduled to be launched from the Russian space center in Baikonur in 2000. PAMELA will search for positrons and antiprotons as well as heavy antinuclei using a system that is more sophisticated than the one built into the AMS. PAMELA will collect fewer cosmic rays, however, because of its small size, so it may not be able to conduct a thorough search for heavy antiparticles.

More balloon-borne searches for cosmic antimatter are on the horizon. For example, we are building a new version of the HEAT detector designed to look for high-energy antiprotons. We hope to improve our measurements by increasing the amount of time the detector remains aloft. NASA has launched high-altitude balloons in Antarctica that can fly for 10 to 20 days, traveling in a circle around the South Pole. And the NASA Wallops Island suborbital team is developing new lightweight fabrics for balloons that may allow flights of up to 100 days. Flight tests of balloons constructed from these materials should occur in the next few months.

The search for antimatter in the cosmos has undergone many twists and turns. The earliest experiments were motivated by a desire for symmetry, an eagerness to prove that there are equal amounts of matter and antimatter in the universe. The results, though, have shown a widespread asymmetry. Antimatter detectors have found very few positrons and antiprotons in the cosmic rays and no heavy antiparticles whatsoever. Antistars and antigalaxies might still lurk somewhere in the universe, billions of light-years from our own galaxy. Yet heavy antiparticles from such distant regions would be unlikely to reach the earth, and hunting for them may be a futile task. Nevertheless, the search for positrons and antiprotons may help reveal the nature of dark matter, one of the great mysteries of astrophysics.

The Authors

GREGORY TARLÉ and SIMON P. SWORDY have both been conducting cosmic-ray research for more than 20 years. Tarlé, a professor of physics at the University of Michigan, earned his doctorate from the University of California, Berkeley, in 1978. He is also active in experiments to search for magnetic monopoles, cosmic neutrinos and neutrino oscillations. Swordy, a professor at the University of Chicago, received his Ph.D. from the University of Bristol in 1979. He was a member of the team of investigators for the Cosmic Ray Nuclei Experiment, which flew on the space shuttle in 1985.

Further Reading

The Early Universe. Edward W. Kolb and Michael S. Turner. Addison-Wesley, 1990.

Cosmic Rays at the Energy Frontier. James W. Cronin, Thomas K. Gaisser and Simon P. Swordy in *Scientific American*, Vol. 276, No. 1, pages 44–49; January 1997.

Constraints on the Intergalactic Transport of Cosmic Rays. Fred C. Adams et al. in *Astrophysical Journal*, Vol. 491, pages 6–12; December 10, 1997.

Information on the HEAT experiment can be found at http://tigger.physics.lsa.umich.edu/www/heat/heat.html on the World Wide Web.

Information on the AMS experiment can be found at http://hpl3sn05.cern.ch:8080/ams01.html on the World Wide Web.