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Cosmic Rays -- Fast-Flying Fossils From Space

By Christopher Wanjek

The sky is raining bullets. In a teeming downpour, atomic particles traveling nearly the speed of light steadily bombard the earth from destinations unknown. Raindrops of silver and gold, as well as hydrogen, carbon and the like, overflow the reservoirs on satellites and high-altitude balloons. If it weren't for the umbrella of our atmosphere, we'd be soaked.

Most of the harmful radioactive particles do not reach the earth's surface. However, frequent business flyers cruising through the high, thinner atmosphere of the perhaps not-so-friendly skies do pick up a measurable dose of radiation along with their free miles and complimentary bag of nuts.

These radioactive particles are called cosmic rays. Where they come from and how they got so fast (and so energetic) has been a mystery since the day they were discovered in 1912.

Viktor Hess, a German physicist with a penchant for risking his life in precarious balloon contraptions, was the first to record increased levels of cosmic radiation during perilous flights five miles high. At the time, he thought the radiation was coming from a light source, perhaps the sun. So he dubbed the radiation "höhenstrahlung," German for "high radiation." In the United States, this translated to "cosmic rays" when subsequent experiments showed that although some of the radiation was from the sun, the most energetic radiation was coming from deep in the cosmos. Years later, scientists realized the radiation was from atomic particles. Too late, though: The name "cosmic ray" had stuck.

Cosmic rays come in many flavors. The most common is the nucleus of hydrogen, simply known as a proton. Others complete the alphabet of the periodic table. These are the nuclei of carbon and nitrogen, up through zinc and uranium. These nuclei were stripped of their electrons from some great upheaval and accelerated to near light-speed. Electrons themselves constitute a small number of cosmic rays, about a 100 times less common than protons.

Today, more so than any other time this century, scientists are planning a flurry of detectors for ground-based, balloon-borne and space observations of cosmic rays. The end goal is to understand the origin of these cosmic bullets, to find the smoking gun. And along the way, these scientists hope to learn what the fast-flying fossils from space say about possible pockets of antimatter in the universe, the distribution and density of "regular" matter, and the limits of energy. All of these secrets hide in the kernel of the cosmic ray.

Dizzy Cosmic Rays

We all know that the shortest distance between two points is a straight line. The problem is that cosmic rays don't play that game.

Starlight is far more affable. Star light travels directly from the star to us, with an occasional bow to Einstein when its path is altered slightly due to the gravitational pull of a black hole or galaxy. Cosmic rays, however, are charged particles. This means they swirl about space influenced by a multitude of magnetic fields. They may have even swung around an entire galaxy a few times before breaking free on a slingshot towards us.

As they near our planet, cosmic rays are influenced by the Earth's own magnetic fields. This is particularly true for the weaker, lower-energy cosmic rays. They funnel towards Earth at the poles, as if on a cosmic ray slide forged by the magnetic fields. Scientists can catch the dizzy cosmic rays, but there are few clues to their origin other than the handful that come from the sun.

Every Cloud Has Silver...

Cosmic rays from the sun are easy to identify. They are mostly very low-energy protons associated with the ebb and flow of solar activity. Theirs is an exclusive club. Other lower-energy cosmic rays from beyond the sun are not allowed in to the solar system. If these weak particles do manage to escape their host galaxies, they are blocked by the magnetic field that surrounds the solar system. However, higher-energy cosmic rays of all delights do break free from their regions of origin. These are the ones that scientists are furiously investigating.

Of course, what better place to look for raindrops than in a cloud. The leading theory of higher-energy cosmic ray origin is that these cosmic rays start their journey in supernova remnants -- clouds of gas produced from an exploded star.

The supernova remnant itself is a warehouse of fusion products that are priced to move. Lighter elements produced in the star's core (such as carbon and helium) are expelled into the surrounding space with immaculate force, colliding and fusing into heavier elements (such as gold and silver). Intense heat sets free swarms of electrons, creating charged particles -- particles with unequal numbers of protons and electrons and thus leaning either to the positive or negative side.

In 1995, the Japanese satellite ASCA observed electrons accelerated to cosmic ray energies in Supernova 1006. Although the observation said little about what produced the electrons in the first place, this was evidence that a supernova shock wave could accelerate matter. In 1999, a team of Argentinean astrophysicists (Combi, et al) found evidence of protons escaping a star explosion in another, newly discovered supernova. The protons likely originated in the star explosion.

If indeed cosmic rays are born in supernovae, would they come flying out like shrapnel? Probably not, according to 1999 results from the Advanced Composition Explorer. Scientists (Hink, et al.) studied nickel-cobalt ratios. A common isotope of nickel, ^{59}Ni, is produced in supernova explosions. This radioactive isotope ultimately decays to the more stable ^{59}Co; its half-life is 75,000 years. The team found in their cosmic ray collection that this decay process had already run its course. This means that ^{59}Ni, formed in one supernova explosion, sat decaying for over a 100,000 years before some other great force -- perhaps the shock wave of a second supernova explosion --propelled it into the surrounding galaxy at cosmic ray energies.

The Cosmic Ray Alphabet Soup

Scientists will never be able to point to an exact source for a given comic ray. By collecting a wide variety of particles, however, they will be able to determine the types of cataclysmic event that produced them, as well as the intervening matter that they passed through on their journey to Earth. The types of cosmic rays read like a spoonful of alphabet soup: C, B, Be, Ni, Co... Like fossils, cosmic rays have stories to tell.

ACCESS (Advanced Cosmic Ray Composition Experiment) will be renting real estate on the International Space Station starting in 2006, collecting cosmic rays from hydrogen (H) all the way up through uranium (U).

Other cosmic ray experiments, such as ISOMAX (Isotope Magnet Experiment), fly regularly on high-altitude balloons toppling 99% of the atmosphere, collecting a narrower range of cosmic rays. Interesting patterns emerge from the ratios of these collected cosmic rays.

ACCESS will be looking for the carbon-boron ratio (C-B), which can tell us how much dust and gas carbon cosmic rays travel through on their way to Earth. A low amount of C compared to B means that the carbon particles traveled through dense matter, smashing into other particles along the way and creating more boron. ISOMAX, which flies this summer, searches for an isotope of beryllium called ^{10}Be. Like the familiar carbon-14, ^{10}Be serves as a clock to date cosmic history. ^{10}Be ratios can reveal how long it take for cosmic rays to reach the Earth, how much matter they travel through, and what portions of their time are spent in our galaxy and outside, in the galactic halo.

This is all precious information about matter that a telescope survey could easily miss. Thus, cosmic-ray studies aid in the search for the Universe's missing baryon matter (protons and such predicted by the big bang yet not seen) and dark matter, that mysterious undetectable matter that comprises over 90% of the universe's mass.

Also, the distribution of elements that ACCESS will collect mirrors the distribution of elements in the Milky Way itself. In fact, cosmic rays are the only fresh particle samples we have from outside our solar system; comets and meteors all originate very close to home. Cosmic rays can be relatively young, only a few million years old, telling us something about the modern Universe -- as opposed to billion-year-old meteors, fossils from a much early era.

The Meanest Cosmic Rays...

Scientists have yet to find an upper limit to cosmic ray energy. In fact, there are some cosmic rays so energetic, at 10^20 electron volts, that they make no sense. It's somewhat of a Catch-22.

"These cosmic rays shouldn't exist," said Dr. Robert Streimatter, a NASA scientist involved in several cosmic ray experiments. "Anything that energetic had to have come from within 150 million light years, because anything traveling farther would have lost its energy during the long trip. Yet nothing known within 150 million light years could produce a 10^20 electron-volt particle."

These most energetic particles pack the sting of a major league fast ball. Seeing how there are as many tiny atomic particles to a baseball as there are baseballs to the moon, that's one powerful pitch. At 10^20 electron volts, these particles have enough kinetic energy to knock a person down. Although the highest energy cosmic rays are rare -- perhaps striking once per square kilometer per century -- there is no denying they exist.

Case in point: On October 15, 1991, one such rare event struck the "Fly's Eye" cosmic ray detector at the Dugway Proving Grounds high in the Utah desert, about 75 miles southwest of Salt Lake City. The particle was clearly strong enough to ignore the magnetic field pulling feeble cosmic rays to the poles. The particle, likely carbon, produced a cascade of over 200 billion secondary particles in the atmosphere, which the Fly's Eye detected. With our powerful Sun spitting out cosmic rays of a mere 10^8 electron volts, a trillion times weaker than this episode, the source of this bullet seems beyond comprehension. On December 3, 1993, another killer cosmic ray struck above Akeno, Japan, at the AGASA detector, not too far from Tokyo. This showed that the most energetic cosmic rays are not a fluke.

The concept of cosmic rays carrying more energy than anything known in the Universe has inspired physicists to construct a new generation of detectors, on the ground and in orbit. The Pierre Auger Project involves 3,200 ground-based detector stations -- half in Utah and half in Argentina -- which will cover an area the size of Rhode Island at both locations. By monitoring particle cascades caused by cosmic rays interacting with the atmosphere, the Auger Project hopes to catch 40 of these monsters per year at its first installation, in Argentina.

NASA's OWL (Orbiting Wide-angle Light collectors) mission hopes to see several thousand of the highest energy cosmic rays per year from space. OWL will view the cosmic-ray-induced fluorescence in the atmosphere from above instead of below, monitoring an area larger than the United States. Because these highest-energy cosmic rays are so powerful, they are not influenced much by magnetic fields. OWL will therefore pinpoint an arrival direction to within one degree.

An OWL launch is still several years off. This summer members of the OWL team will fly an experiment called NITE GLOW on a high-altitude balloon to measure ultraviolet background light in the atmosphere, which will be essential to the OWL design. The OWL technology might provided the deepest probe yet to the early Universe. The origin of the highest energy cosmic rays may trace back to topological defects in the structure of spacetime when the Universe was only 10^{-35} of a second old.

What's the Matter with Antimatter...

Antimatter is not science fiction. It's real and it comes to us in the form of cosmic rays. The question is, why isn't there more of it?

Antimatter has properties that mirror the particles that compose ordinary matter, such as human bodies and the Earth. Ordinary matter is made of protons with a positive charge, neutrons with zero charge and electrons with a negative charge. Antimatter would be composed of negatively charged antiprotons, antineutrons and positively charged antielectrons (or positrons). When matter and antimatter meet, they annihilate. No "ash" is left over. This is a 100% efficient process, as opposed to the 1% efficiency of a nuclear fusion reaction.

According to the big bang theory, equal amounts of matter and antimatter should have been created in that initial grand spark. Scientists, however, have been hard-pressed to find this antimatter. Our neck of the woods seems to be to be filled with that boring regular stuff. The antimatter that scientists do see is not a relic of the big bang. Rather, they are secondary particles created by collisions of ordinary matter in the interstellar medium -- essentially antiprotons and positrons.

Evidence of an antimatter galaxy would be the detection of anti-helium, which couldn't easily be made in a particle collision like anti-hydrogen (the antiproton). Such a discovery would be stunning. Every summer, NASA launches a 60-story balloon to search for antimatter with a Japanese-built instrument called BESS (Balloon-borne Experiment with a Superconducting Solenoidal Magnet). Each year BESS collects those antiprotons, but it has yet to find anti-helium. BESS is now at a point of not finding anti-helium in a sample over a million helium particles.

The International Space Station will be home to an antimatter bucket built by Nobel Prize physics laureate Samuel Ting. Is this but a futile search? Russian physicist Andrei Sakharov proposed three conditions in 1967 that, if met, would allow a predominance of matter over antimatter in the early Universe. In the decades that have followed Sakharov's proposal, physicists have found ways for each of these proposals to be met -- at least in the laboratory. Still, Jonathan Ormes, a NASA Goddard astrophysicist, is among many who dig through the annual BESS data with childlike anticipation. "We are very excited every year when we check the latest data hoping to find the first 'Ambassador from the Anti-World,'" he says.

Nature Is Telling Us Something...

From the rarest to the most energetic that nature has to offer, cosmic rays are an enigma. Closer to home, the cosmic rays produced by the sun have taught us much about the Sun-Earth connection. Yet farther out in space, cosmic rays sting us with the realization that so little is known about the nature of matter and energy. No single cosmic ray detector will answer all of our questions. The endeavor to understand the physics and origin of cosmic rays will take a variety of detectors, as well as X-ray and gamma-ray observatories that track their path across galaxies.

These fast-flying fossils have traveled the lengths of the Universe, whirling and twirling through stardust along the way. They are lapped with the bumper stickers of extragalactic travel. Surely there's a lesson to be learned here, and scientists are set on finding it.

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