

Messages from the dark side?



De HESS-telescoop, waarmee gammastraling uit het Melkwegcentrum is onderzocht.

Astronomers have detected gamma rays that might come from dark matter smashing itself to smithereens.

Want to see a mystery? Don your gamma-ray goggles and look up. You'll glimpse many bright gamma-ray sources, such as supernova remnants, that are well understood. But you'll also notice a diffuse, roughly circular, low-energy glow centered on the core of our Milky Way Galaxy. No one knows where it comes from.

The same holds true for a much smaller source of very-high-energy gamma rays smack dab in the galactic center. Furthermore, the entire sky is just a wee bit brighter in medium-energy gamma rays than expected. Astronomers and physicists alike are determined to solve these multiple gamma-ray mysteries, because the solutions may tell us something about dark matter.

From observing the rotation rates of spiral galaxies and the motions of galaxies within clusters, astronomers have good reason to think that about 85% of the universe's material content produces gravity but no light. Nobody knows its true nature. Does this enigmatic dark matter consist of new types of particles? Does it leave any observable trace? Perhaps it does, in the form of these three different types of gamma-ray emission that have defied conventional explanation.

Antimatter Annihilation

Even if gamma-ray goggles actually existed, you couldn't see the Milky Way's mysterious glow from your backyard. Life exists on Earth because the atmosphere absorbs this lethal radiation — the most energetic photons in the electromagnetic spectrum. Gamma rays can be spotted directly only by instruments on high-altitude balloons, sounding rockets, and spacecraft.

Thus it wasn't until the early 1970s that astronomers detected gamma rays from the galactic center, which turned out to have a specific energy, or gamma-ray "color," of 511 kiloelectron-volts (keV) — a millionth the kinetic energy of a flying mosquito. That might not sound like much, but it's hundreds of thousands of times more energetic than a visible-light photon.

Laboratory experiments have shown that 511-keV emission is the telltale signal of electrons colliding with their antimatter counterparts: positrons. When matching particles of matter and antimatter meet, they annihilate each other and convert their mass into gamma rays according to Einstein's famous equation $E = mc^2$.

The astronomical data indicate that a staggering 1050 positrons are annihilated each year in the galactic center — about an Earth's worth of antimatter every 100,000 years. Where does all of this stuff come from? Nuclear reactions in supernovae and collisions of cosmic-ray particles with interstellar gas produce positrons, but any gamma-ray glow resulting from such processes would closely follow the distribution of stars or gas. That's very different from the almost circular patch mapped in 2003 by the European Space Agency's Integral satellite.

But the smooth, concentrated glow is exactly what a team led by Oxford University physicists Celine Boehm and Dan Hooper predicted in 2003 if annihilating dark-matter particles produce the positrons. Just like our familiar matter made of atoms, dark matter feels gravity, so it should settle into the galactic core. Furthermore, theory suggests that dark-matter particles are their own antiparticles, so in their rare collisions with one another they annihilate. Calculations further show that electrons and positrons are produced, along with photons and neutrinos. The electrons and positrons in turn run into one another, producing the 511-keV glow. According to Boehm and Hooper, the galactic center's gamma-ray glow could be the fingerprint of dark matter.

A Contradiction

Many physicists think that dark matter consists of weakly interacting massive particles (WIMPs). Supersymmetry, a promising theory for extending the highly successful Standard Model of particle physics, predicts the existence of "supersymmetric partners" for each known particle. WIMPs represent a class of partners that weigh a few hundred thousand or even a few million times more than electrons. Being heavy particles, WIMPs feel and exert gravity, but that's about the only way they interact with familiar matter. Since they are immune to electromagnetism, they don't emit or reflect any form of radiation.

But the dark-matter particles envisioned by Boehm and Hooper (now at the Laboratory for Theoretical Physics in France and Fermilab in Illinois, respectively) must be relatively light: at most 200 times the mass of an electron. If the particles were heftier, their annihilations would produce unstable types of matter and antimatter particles. As they decay they would generate far more gamma rays than astronomers have observed.

According to physicists John Beacom and Hasan Yksel (Ohio State University), the dark-matter particles implied by Boehm and Hooper's theory must actually weigh less than a scant 6 electron masses. Beacom and Yksel point out that positrons and electrons resulting from annihilating dark matter also produce gamma rays with energies higher than 511 keV. This radiation is stronger for more massive dark-matter particles. But gamma-ray observatories have not detected it. So if the 511-keV signal has anything to do with dark matter, the mysterious particles must be very lightweight indeed.

Meanwhile, astronomers Kyungjin Ahn and Eiichiro Komatsu (University of Texas, Austin) have calculated the expected strength of the extragalactic gamma-ray background, assuming that all dark-matter halos around distant galaxies produce 511-keV radiation through the process suggested by Boehm and Hooper. They found that this background should be stronger than observed unless the dark-matter particles weigh more than about 40 electron masses. Their argument is straightforward: a lower mass means a larger number of particles for the same total amount of cosmic dark matter, so they would produce more positrons and electrons, resulting in a stronger signal.

And therein lies a contradiction. A particle cannot simultaneously weigh less than 6 electron masses and more than 40 electron masses. Hooper concedes that his and Boehm's dark-matter concept, which was greeted with enthusiasm in 2003, now appears to be "less attractive," but he notes that Ahn and Komatsu's conclusions depend strongly on the distribution of dark matter in our galaxy and others. He also says there's no better idea to explain the 511-keV mystery.

The HESS Mystery

And that's not the entire gamma-ray story. The High-Energy Stereoscopic System (HESS) has recently observed extremely high-energy gamma-ray photons (each packing a few hundred billion electron volts) from the galactic center. Could this signal be related to dark matter? Maybe, says Ahn, but that interpretation would still be difficult to reconcile with current thinking about WIMPs, the most likely candidates for dark matter.

HESS is a new array of four 13-meter light buckets in Namibia for the study of ultra-high-energy gamma rays. Like all gamma rays, these energetic photons cannot be observed directly from the ground. Instead, HESS detects very faint streaks of light (known as Cherenkov radiation) that are produced when these gamma rays hit Earth's atmosphere. In 2004 a large collaboration of HESS researchers reported the detection of a strong point source of these energetic gamma rays coincident with our galactic core.

The source of this radiation is unknown, but according to an analysis by HESS team member Dieter Horns, it could be produced by dark-matter particles annihilating and producing unstable particles that produce high-energy gamma rays as they decay. But the dark-matter particles would have to be extremely massive, about 20,000 times the mass of a proton (40 million electron masses). Some particles predicted by supersymmetry may be that massive, says Ahn, but the HESS observations would pose a problem for the most popular supersymmetric dark-matter candidate particle, the neutralino, which is predicted to be less than 1,000 proton masses. Also, the gamma

rays energy distribution does not match the characteristic features predicted for dark-matter annihilation.

A Third Signal

Like other scientists, particle physicist Wim de Boer (University of Karlsruhe, Germany) thinks that astrophysical processes in the galactic core involving supernovae, neutron stars, or black holes might explain these energetic gamma rays. He also thinks that's the case for the lower-energy 511-keV signal. But in a recent series of papers, he claims that a third gamma-ray signal from the Milky Way bears a dark-matter fingerprint after all.

Working with publicly available data from NASA's Compton Gamma Ray Observatory, de Boer and two colleagues analyzed an excess of medium-energy gamma rays observed by the satellite's Energetic Gamma Ray Experiment Telescope in the 1990s. EGRET detected a faint background of gamma rays with energies between 30 million and 10 billion electron volts between the "soft" 511-keV signal and the "hard" HESS signal. The most likely sources of these medium-energy gamma rays are energetic cosmic-ray particles colliding with atomic nuclei in interstellar space. But the EGRET signal was a lot stronger than expected.

According to de Boer, the excess can be readily explained by the annihilation of dark-matter particles having 60 times the mass of a proton. From EGRET's all-sky maps he deduced the galactic distribution of these dark-matter particles, calculated their gravitational influence, and predicted the shape of the Milky Way's rotation curve the plot showing the relationship between orbital velocities of stars and their distances from the galactic center. The agreement with the observed rotation curve is striking: the calculations even reproduce a hitherto unexplained "kink" in the curve 35,000 light-years from the center.

Horror Scenario

So are EGRET's observations telling us something about the elusive dark matter? Probably not, says theoretical physicist Lars Bergström (Stockholm University, Sweden). A 60-proton-mass dark-matter particle may sound like a gift from the sky to supersymmetry theorists since the predicted neutralino mass lies in this neighborhood. But the annihilation of these massive particles should also produce protons and their antimatter counterparts: antiprotons. As a result, antiprotons should be observed in rather large numbers by cosmic-ray detectors flying on high-altitude balloons. But they aren't. Instead, Bergström argues that EGRET's observed excess can be fully accounted for by cosmic rays, whose numbers and properties may vary throughout our galaxy.

Like de Boer, Bergström is skeptical about the dark-matter interpretation of the 511-keV and HESS signals. There may be no relation between galactic gamma rays and dark matter. After all, dark matter need not necessarily annihilate into particles. For instance, one exotic candidate dark-matter particle, the gravitino (the supersymmetric partner of the graviton, which carries the gravitational force), may interact so weakly that it hardly annihilates at all. Gravitino dark matter, says Bergström, is in some sense a horror scenario, since astronomers and particle physicists may never be able to detect it directly.

So the multiple gamma-ray mysteries remain unsolved . . . for now. High-energy-astrophysicists look forward to the August 2007 launch of NASA's Gamma-ray Large Area Space Telescope (GLAST). Its instruments are 50 times more sensitive than EGRET and cover a much wider energy range, up to a few hundred billion electron volts. GLAST may enable astronomers to solve the riddle once and for all.

Meanwhile, a powerful new accelerator known as the Large Hadron Collider is nearing completion at CERN, the European center for particle physics in Geneva, Switzerland. This facility, also due to become operational in 2007, might detect supersymmetry particles directly. So will the first convincing data on dark-matter properties be gained by astronomers or by particle physicists? It's hard to predict, but the race is on.

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