

An Array of Cherenkov Telescopes Yields the First Resolved Image of a Celestial Gamma-Ray Source

Imaging with TeV photons provides the most direct evidence yet that cosmic rays originate in the shock fronts of supernova remnants.

Almost all primary cosmic rays are charged particles—mostly protons. But the one primary in a thousand that's a gamma has special value for astrophysicists. The arrival direction of a charged particle of energy less than 10^{18} eV reveals nothing about where it came from. That's because the random microgauss magnetic field pervading the galaxy thoroughly scrambles the trajectories of all but the most ultrahigh-energy charged particles (which are presumed to originate somewhere beyond the galaxy). But gammas, being impervious to magnetic fields, are superb astrophysical pointers.

What is the astrophysical mechanism that accelerates charged particles to the TeV (10^{12} eV) energies typical of high-energy cosmic rays that originate in our galaxy? The general presumption is that the particles are accelerated by the moving magnetic fields caught up in the remnant shock fronts created by supernova explosions. But until now, the evidence for that mechanism has only been indirect.

Imaging with TeV gammas

TeV gammas, as far as anyone knows, can be made only by charged particles of even higher energy. The two most likely sources of TeV gammas are the prompt decay of neutral pions produced in collisions of high-energy protons with interstellar material and the inverse Compton scattering of high-energy electrons off ambient low-energy photons. (About 1% of cosmic-ray primaries are electrons.)

A new imaging technology has now provided the most direct evidence yet that TeV gammas, and therefore the

high-energy protons and electrons that make them, do indeed originate in the expanding remnant shells left over by long-dead supernovae. A European collaboration has published the first resolved image of a celestial gamma-ray source.¹ Using the new High Energy Stereoscopic System (HESS), an array of four Cherenkov telescopes sitting at an altitude of 1.8 kilometers in central Namibia, the collaboration has imaged the shell of a thousand-year-old supernova remnant in TeV gammas (see figure 1).

The high-energy gammas themselves never make it to the ground. What the HESS telescopes (shown in figure 2) record is the flash of Cherenkov light generated by the shower of relativistic electrons and positrons created when an energetic gamma hits the upper atmosphere. From the Cherenkov light, one can determine the primary gamma's direction within a few arcminutes, and its energy within about 15%. The higher the primary's energy, the more light it produces. The minimum primary energy for a Cherenkov telescope, depending somewhat on the altitude at which it sits, is about 0.1 TeV.

The Southern Hemisphere remnant, labeled RX J1713.7–3946, was discovered and imaged in x rays in 1996. Four years later, it was identified, but not resolved, as a source of TeV gammas by the Australian–Japanese CANGAROO collaboration.² This particular supernova remnant, about 3000 light-years away, had attracted attention because

molecular clouds were abundant in its vicinity and because the nonthermal component of its x-ray output was unusually strong.

The contour lines superposed on the HESS image in figure 1 show the remnant's x-ray brightness distribution as imaged in keV x rays by Japan's ASCA satellite. The comparison makes it clear that, for the most part, the TeV and keV photons are coming from the same regions of the remnant's outer shell.

Cherenkov telescopes have been unambiguously identifying supernova remnants, starting with the Crab nebula, as discrete sources of TeV gammas since the late 1980s. But until now, there has been no resolved gamma image. It was impossible to associate the gamma source with specific morphological features of a supernova remnant as seen in visible light or x rays. The CANGAROO group's Cherenkov telescope could identify only a diffuse patch of TeV gammas in RX J1713.7–3946.

A new generation

The HESS facility is the first of a new generation of Cherenkov telescope complexes that have the potential to image gamma sources. Its name, aside from the acronymic meaning, celebrates Victor Hess, the discoverer of cosmic radiation (see the photo, on page 43, of Hess aboard a balloon in 1912). The collaboration, whose largest contingents are German and French, is led by Werner Hofmann of the Max Planck Institute

Figure 1. Gamma-ray image of the supernova remnant RX J1713.7–3946 obtained with the Cherenkov telescopes of the new High Energy Stereoscopic System (HESS). The color key indicates the number of recorded gamma showers per unit circle of radius 5 arcminutes, the resolution of this image. The incident energies of the gammas whose showers were used to make the image ranged from 0.8–10 TeV. The contour lines represent the keV x-ray brightness of the remnant as measured by Japan's ASCA satellite. (Adapted from ref. 1.)

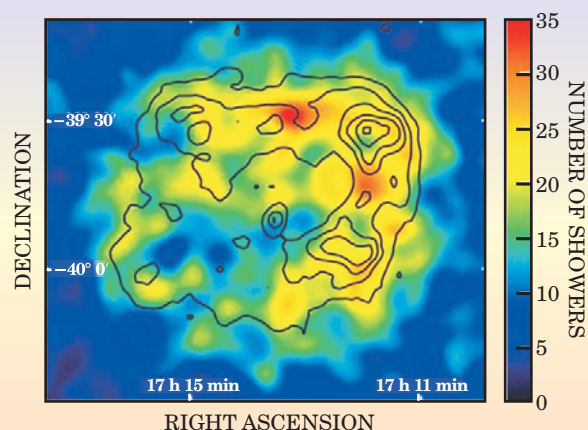




Figure 2. The four Cherenkov telescopes of the recently completed HESS facility sitting at an altitude of 1.8 km in Namibia's Khoma Highland. Each telescope's segmented 13-meter-diameter parabolic reflector directs the flash of Cherenkov light from an incident high-energy cosmic-ray shower onto the focal-plane array of phototubes that serves as its high-speed camera. (Courtesy of the HESS collaboration.)

for Nuclear Physics in Heidelberg.

A competing US project, called VERITAS, plans to have four Cherenkov telescopes on Kitt Peak in Arizona by 2006. "They've scooped us with this unprecedented image," says project leader Trevor Weekes of the Whipple Observatory. "We were the first to propose such a facility, but we've had funding difficulties."

The HESS telescopes, spaced at the four corners of a field 120 m on a side, provide a stereoscopic quartet of views that refines the determination of the primary gamma's direction enough to yield useful images. The fleeting Cherenkov light from a shower generated by a TeV gamma hits the ground with a spot diameter of a few hundred meters. Each telescope collects its share of the Cherenkov flash with a segmented 13-meter-diameter parabolic reflector that directs the light onto a 960-phototube focal-plane camera. The shower spreads out conically about 1° from the incoming TeV gamma. But multiple stereoscopic views fix the shower's axis and thus the primary's direction to within 2 or 3 arcminutes. That sets the resolution limit of the gamma image. Producing such an image requires extensive off-line analysis to translate each raw shower into a single image point.

HESS's stereoscopic imaging also makes it easier to distinguish the desired gamma-induced showers from the much larger number initiated by cosmic-ray protons. With their many pions and muons, showers initiated

by high-energy protons are wider and vertically longer than gamma-induced showers. The lower the primary's energy, the harder it is to make this crucial distinction reliably.

Figure 1, the published remnant image, was produced from 26 total hours of exposure with only two telescopes during a construction and commissioning phase in 2003. To minimize the background of proton showers mistaken for gammas with the stereoscopic discrimination thus limited, the collaboration chose to produce this first gamma image with a cautious low-energy cutoff of 0.8 TeV. The upper energy limit of about 10 TeV for Cherenkov telescopes is imposed by the steep decline of cosmic-ray flux with increasing energy (see figure 3). For higher-energy regimes, one needs long exposure times or shower detector arrays covering very large areas.

Electrons or protons?

"All four telescopes are now fully operational," says Hofmann, "and we will soon have images of RX J1713.7–3946 with improved resolution and photon statistics." What can one expect to learn from those sharper images? It's already clear that the TeV gammas are coming, as expected, from the expanding shell of the supernova rem-

nant rather than from some exotic source at its core. The question of greatest interest for cosmic-ray physics is whether the shell population of high-energy charged particles that created the TeV gammas is predominantly protons or electrons.

One could already have concluded from the remnant's x-ray image and spectrum that the shell must contain an abundance of high-energy electrons. The strong nonthermal component of the x-ray spectrum implies that most of the x-ray photons come not from hot ionized material or bremsstrahlung, but rather from synchrotron radiation by multi-TeV electrons spiraling in the remnant's magnetic field. Such electrons are also energetic enough to kick ambient photons up to TeV energies.

Is there enough of this inverse Compton scattering to account for all the TeV gammas from RX J1713.7–3946? "If the x-ray and gamma spatial distributions are similar enough," says Hofmann, "and we can reproduce their relative intensities by twiddling the unknown magnetic field, multi-TeV electrons could possibly be the whole answer. But our data aren't yet precise enough."

The principal alternative source of TeV gammas, and the one that bears most directly on the preponderant

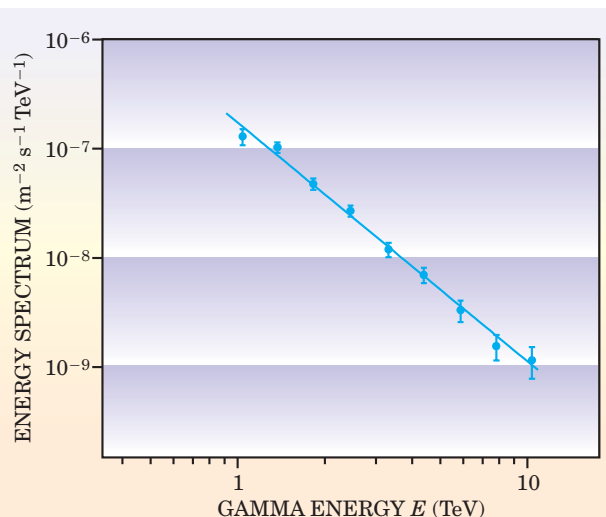


Figure 3. Gamma energy spectrum of the supernova remnant RX J1713.7–3946 as measured by the HESS Cherenkov telescopes. Below 1 TeV, distinguishing the rare cosmic-ray showers initiated by gammas from the much larger background of proton-induced showers becomes increasingly difficult. Above 10 TeV, short exposures run out of showers. The line represents the best power-law (E^{-P}) fit to the data, giving $P = 2.19 \pm 0.2$. (Adapted from ref. 1.)

proton component of cosmic rays, is the two-gamma decay of neutral pions created by multi-TeV protons colliding with molecules such as H_2 and CO . That mechanism would account straightforwardly for the $E^{-2.2}$ falloff of the gamma energy spectrum shown in figure 3. But appraising the contribution of high-energy proton collisions to RX J1713.7–3946's gamma output requires comparing the gamma image with the distribution of molecular clouds in the remnant's vicinity. One problem is that the radio-telescope surveys that trace such clouds by tell-tale molecular transition lines yield only column densities. That is, they cannot easily distinguish clouds at the

shock front from foreground clouds along the line of sight. "It's still a work in progress," says Hofmann.

The shock front's velocity, expressed as β , its fraction of the speed of light, is only about 3%. A charged proton or electron traversing the shock front can acquire a fractional energy gain of about β from the moving magnetic field. That might seem like far too timid a kick to account for TeV cosmic rays. The standard answer is that the very few charged particles that make it to TeV energies not only start out in the high-energy tail of the thermal distribution. They also have to traverse the same shock front hundreds of times. That improbable fate can befall a particle if random

scattering off ambient material reverses its direction often enough without dissipating its accumulating energy.

It's a very slow process. The lucky few typically take thousands of years to reach TeV energies. Supernova shock fronts last for tens of thousands of years before they run out of steam. Perhaps half of their initial energy eventually ends up in cosmic rays.

Bertram Schwarzschild

References

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New Study Correlates Mantle Melting to Mid-Ocean Ridge Segments

Variations found in the composition along a stretch of exposed mantle on the Arabian peninsula offer fresh evidence for the link between the length scale of ridge segments and Earth's convection process.

The mid-ocean ridge is a 75 000-kilometer network of undersea mountain chains that, like the seam of a baseball, winds around the globe from the Arctic Ocean to the Atlantic, around Africa, Asia, and Australia, under the Pacific, and skirts the west coast of North America. This fundamental feature of Earth's superstructure delimits the intersection of tectonic plates and is the source of 85% of Earth's volcanism. As plates separate and cracks form, the mantle wells up to fill the gap. Partial melting of the solid mantle produces magma that percolates upward through pores and grain boundaries in the rock and then crystallizes into basalt—new layers of

Earth's crust. The process prompted oceanographer Bruce Heezen to characterize the ridge system as "the wound that never heals."

But if the mechanics of tectonic fracture were all that controlled the accretion of crust, one might expect uniform depth everywhere as the plates spread. In fact, the topography of the ridge is rich and varied, with frequent discontinuities and offsets, ranging in length from a few kilometers to hundreds of kilometers, that partition it into segments. Ridge geometry can be complicated, in part because the segments behave like giant, mobile cracks that may lengthen or shorten over time. Never-

theless, they appear to be closely linked to melting in Earth's mantle, based on well-known variations in the petrology, magnetization, and, in some places, the thickness of crust formed beneath the deep oceans along the ridge.

Exactly what accounts for those variations has puzzled researchers for years. Laurent Le Mée, Christophe Monnier, and group leader Jacques Girardeau from the University of Nantes in France have now provided direct evidence for the link between segmentation in ocean ridges and the upwelling process deep underground by studying how the geochemistry of the mantle itself varies along the ridge axis.¹

Rock and magma

The problem of determining how the production and transport of heat and

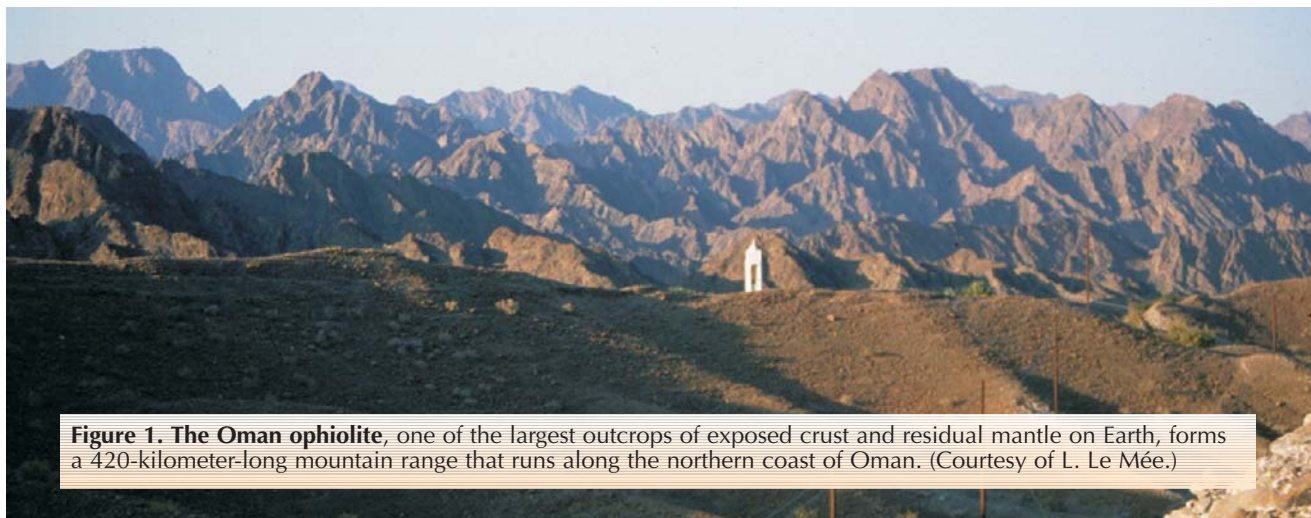


Figure 1. The Oman ophiolite, one of the largest outcrops of exposed crust and residual mantle on Earth, forms a 420-kilometer-long mountain range that runs along the northern coast of Oman. (Courtesy of L. Le Mée.)