could attach the NV center to a scanning probe tip. The Stuttgart researchers have already built the setup for the latter approach, Reinhard says, "so I hope the first proof of principle won't take too long."

But the bigger challenge, says Rugar, lies in improving the signal-to-noise ratio enough to detect small numbers of nuclei. At present, the California team's detection volume contains about a million nuclei; the Stuttgart group's, about 10 000. Moving the NV center even closer to the diamond surface would shrink the detection volume, although it would also reduce the defect's coherence time. More efficient detection of the fluorescent photons that reveal the NV center's state would also help. The California researchers estimate that with realistic improvements in both those areas, imaging a molecule atom by atom is a goal within reach.

Johanna Miller

References

1. C. L. Degen et al., *Proc. Natl. Acad. Sci. USA* **106**, 1313 (2009).
2. H. J. Mamin et al., *Science* **339**, 557 (2013).
3. T. Staudacher et al., *Science* **339**, 561 (2013).

Gamma-ray spectra show that supernova remnants create cosmic-ray protons

Spectral signatures of pion decay have long been sought as direct evidence of proton acceleration in supernova shock fronts.

The interstellar cosmic-ray flux is dominated by high-energy protons presumably accelerated by sources within the Milky Way. For decades the best guess as to those intragalactic acceleration sites has been the shock fronts of supernova remnants (SNRs). They're thought to be capable of accelerating ambient protons to energies as high as 10^6 GeV, a million times the proton mass. But the evidence has remained frustratingly indirect.

Now, at last, the collaboration that runs the Large Area Telescope (LAT) aboard the *Fermi Gamma-Ray Space Telescope* has found convincingly direct evidence of proton acceleration to cosmic-ray (CR) energies in two 10 000-year-old SNRs a few thousand light-years away.[1] After four years of data taking and analysis, the gamma-ray spectra of the two SNRs revealed a long-sought signature of abundant pion production, which can't be happening unless the remnants are indeed accelerating protons to CR energies.

Shock-front acceleration

Cosmic-ray protons represent a mean energy density throughout the galaxy roughly equal to that of all the starlight. In 1964 Vitaly Ginzburg argued that the only plausible intragalactic sources abundant and powerful enough to generate so much kinetic energy over time are supernovae. The mechanism by which a supernova might eventually convert a significant fraction of its explosive energy into CR protons had been introduced 15 years earlier by Enrico Fermi. He had conjectured that randomly moving magnetic fields in the interstellar medium could stochastically accelerate protons to CR energies in small increments by bouncing them back and forth for centuries.

The expanding shock fronts of supernova remnants, where the exploding star's ejecta impinge upon the undisturbed interstellar medium, provide strong, turbulent magnetic fields. The Milky Way witnesses a few supernovae per century. Ginzburg pointed out that most of the galaxy's CR flux could be accounted for if something like 10% of a supernova explosion's energy goes to Fermi proton acceleration over perhaps 20 000 years, after which its shock front becomes too attenuated and slow.

Theoretical elaboration of the shock-acceleration scenario in recent decades has strengthened the prediction that many SNRs should be profusely making CR protons. And there is much observational evidence, albeit indirect. For example, the theory predicts that SNR shock fronts should also be accelerating electrons. And indeed, x-ray observations of SNRs show telltale synchrotron radiation from those high-energy electrons.

But electrons represent less than 3% of the galactic CR flux. And because they're so much lighter than protons, they produce gammas much more profusely when they scatter off ambient

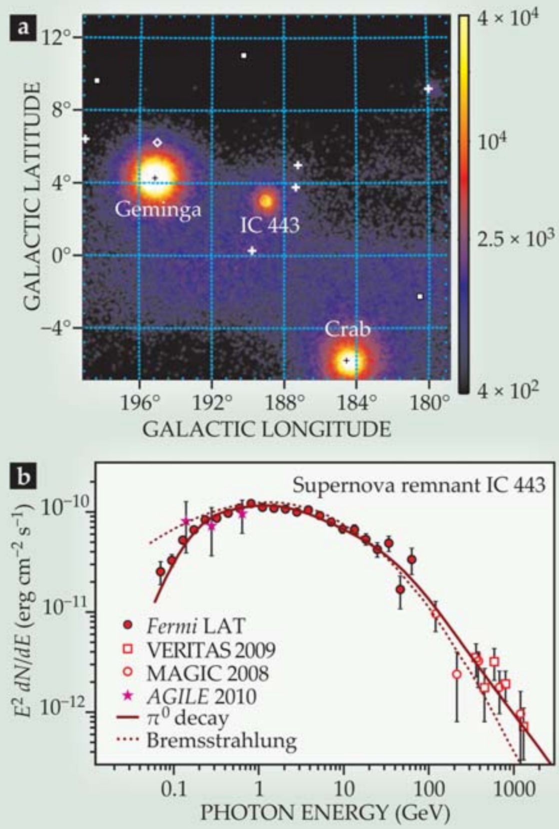

Figure 1. Supernova remnant IC 443, a bright source of gamma radiation. **(a)** Sky map of IC 443's vicinity from observations by the *Fermi Gamma-Ray Space Telescope* is color coded by total gamma-photon counts per $(0.1°)^2$ recorded over four years by *Fermi*'s Large Area Telescope (LAT). Nearby are two other bright sources dominated, unlike IC 443, by pulsar radiation. Marked in white are faint point sources. **(b)** Energy spectrum of IC 443's gamma radiation measured by LAT and other gamma-ray telescopes. The photon-count spectrum dN/dE is multiplied by E^2. Curves show best fits to the LAT data for models assuming only bremsstrahlung from accelerated electrons or only two-gamma decay of neutral pions created by accelerated protons. (Adapted from ref. 1.)

material (bremsstrahlung) or photons (inverse Compton scattering). In SNR spectra, it's been hard to distinguish those electron-generated gammas from the much-desired direct evidence for proton acceleration—namely, gammas from pion decay.

Looking for pion production

Two colliding protons can produce a neutral pion in the reaction

$$p + p \rightarrow p + p + \pi^0,$$

but only if the initial kinetic energy in their center-of-mass reference frame exceeds the 135-MeV pion mass. If the target proton was initially almost at rest, this kinematic requirement translates into a pion-production threshold kinetic energy of 290 MeV for the other one. That's a relativistic energy much higher than one would expect in an SNR's thermal proton population.

So evidence of pion production in an SNR would be evidence of local proton acceleration. How would it show up in the SNR's gamma-ray spectrum? A π^0 decays in less than a femtosecond into two gammas:

$$\pi^0 \rightarrow \gamma + \gamma.$$

In the pion's rest frame, each γ has an energy of 67.5 MeV, half the π^0 mass. But in the hodgepodge of freshly made π^0s moving hither and yon outside the shock front, their clearest signature in the γ spectrum would be a rather abrupt and steep falloff with decreasing energy, beginning at about 250 MeV, relative to what's expected from bremsstrahlung.

But finding that telltale break has been a challenge for observers. Orbiting gamma-ray telescopes determine the energy and direction of an incident γ by recording the electron–positron pairs it generates as it traverses layers of material in the telescope's innards. That pair production, and hence the technique's efficiency and precision, increases with γ energy. Below 250 MeV, it's particularly problematic. There, the Italian Space Agency's pioneering *AGILE* gamma-ray telescope, whose effective aperture is much smaller than LAT's, had been able to garner only very limited spectral data.[2]

The *Fermi* orbiter

Launched into low Earth orbit aboard *Fermi* in 2008, LAT, with its very wide field of view, covers the entire gamma-ray sky, from 20 MeV to 300 GeV, every three hours. (See the article by David Thompson, Seth Digel, and Judith Racusin in PHYSICS TODAY, November 2012, page 39.)

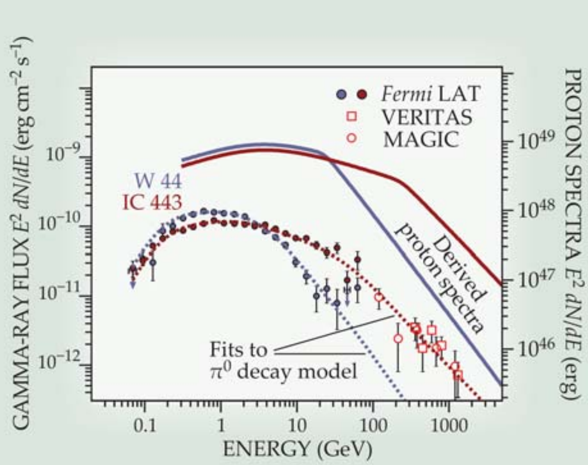

Figure 2. Gamma-ray spectra from supernova remnants (SNRs) IC 443 and W 44, measured by the *Fermi* orbiter's Large Area Telescope and other instruments. The kinetic-energy spectrum for protons accelerated in each SNR is derived from the best π^0-decay model fits to the LAT data. Enough such derived proton spectra should reveal what fraction of the intragalactic cosmic-ray flux originates in SNRs. (Adapted from ref. 1.)

Among the many localized, steady-state γ sources in the four-year LAT data, about 50 have been identified with Milky Way SNRs imaged at optical or radio wavelengths. A LAT team led by Stefan Funk (Stanford University) has concentrated on the two that appear brightest in the gamma-ray sky without being complicated—like the historic Crab SNR—by strong γ radiation from a still-active central neutron star. The nearer of the two, at 5000 light-years, is labeled IC 443 and shown in figure 1a. The other, twice as far away, bears the equally stirring name W 44.

"We tentatively attributed the outstanding brightness of those two to their close proximity to dense molecular clouds that would provide lots of pion-production targets for accelerated protons," says Funk. "And we devoted special effort to determining their γ spectra below 200 MeV, the difficult but crucial regime for distinguishing π^0 decay from bremsstrahlung." Near dense clouds, inverse Compton scattering contributes negligibly to the gamma spectrum below 10^3 GeV.

Figure 1b shows the LAT spectral measurement of IC 443 from 60 MeV to 60 GeV. The two curves are the best fits to the LAT data for two mutually exclusive models: One attributes all the γ radiation from the SNR to the decay of π^0s created by accelerated protons; the other assumes only bremsstrahlung by accelerated electrons. The low-energy data, where the two fitted curves diverge abruptly near 250 MeV, unambiguously favor π^0 decay.

The model curves diverge again, more gradually, toward the spectrum's upper end. But the flux much above 60 GeV is too sparse for LAT. The higher-energy data are from ground-based Cherenkov-telescope arrays, which exploit the atmosphere as a detection medium (see PHYSICS TODAY, January 2005, page 19). But even they have error bars too large to allow meaningful discrimination at high energies. In any case, the W 44 data tell much the same story: "The low-energy γ data have given us direct evidence that *at least* these two SNRs create CR protons," says Funk.

SNR diversity

Fitting the free parameters of the π^0-decay model to the γ spectrum also yields an approximation to the spectrum of the accelerated protons that presumably created the pions. The results for both IC 443 and W 44 are shown in figure 2. Both proton spectra thus derived exhibit abrupt steepening at high energy. But unlike the low-energy break in the γ spectrum that appears to occur at the same 250-MeV energy in both SNRs, the high-energy break in the IC 443 proton spectrum occurs near 200 GeV, ten times higher than the corresponding break in W 44.

The disparity implies that the abrupt steepening of the accelerated-proton spectrum is not attributable to a universal property like the pion-production threshold, which comes simply from particle masses and energy conservation. Differing from one SNR to the next, the proton spectral breaks probably reflect variables like the density of a nearby gas cloud or the maximum accelerating capacity of a given shock front, which wanes with age.

Given that irreducible variability, "LAT will have to harvest a lot of data from other supernova remnants over the next five or so years," says Funk, "before we can seriously estimate what fraction of the total galactic cosmic-ray flux is accelerated in their shock fronts."

Another central question is whether SNRs can really accelerate protons all the way up to 10^6 GeV, where a prominent kink (the so-called knee) in the overall CR spectrum is thought to mark the transition to higher-energy protons coming from beyond our galaxy. "For the answer to that one," says Funk, "we'll have to rely on ground-based arrays of Cherenkov telescopes and water tanks" now under construction[3] or on drawing boards.

Bertram Schwarzschild

References

1. M. Ackermann et al. (Fermi LAT collaboration), *Science* **339**, 807 (2013).
2. A. Giuliani et al., *Astrophys. J.* **742**, L30 (2011).
3. See, for example, the HAWC collaboration, http://www.hawc-observatory.org.

Earth's land surface temperature trends: A new approach confirms previous results

The newcomers to the task looked at many more weather stations and used a geostatistics technique to adjust for data discontinuities.

People have been measuring and recording temperatures since the 17th century, and scientists have been using those data to estimate a mean global temperature since the late 19th century. As weather stations increased in precision and in global coverage, especially in the last half of the 20th century, they facilitated better estimates of the mean global temperature—a key indicator of possible climate change.

For the past 30 years, those estimates have primarily been done by three independent teams: the Climatic Research Unit[1] (CRU) of the University of East Anglia in the UK, in collaboration with the Hadley Center of the UK Met Office; NASA's Goddard Institute for Space Studies[2] (GISS); and the National Oceanic and Atmospheric Administration's National Climatic Data Center[3] (NCDC).

Their task is not a simple one. For decades, researchers have compiled databases of historic temperature records from disparate sources in more than 100 countries. Analysts must correct those raw data for discontinuities in a given station's time series caused by factors unrelated to climate, such as installation of an instrument, a move to a new location, or changes in recording practices. Next they must sort the global trend from the expected local weather fluctuations. In addition, they must account for the uneven global coverage, with more plentiful data from North America, for example, than from Africa. Despite different approaches to those tasks, the three main groups have produced consistent results: All report an increase in the global temperature over the past century.

Given the importance of the temperature trends to the climate discussion, critics have focused on possible biases from such factors as data selection or the urban heat island effect—the warming experienced by some weather stations as the surrounding area becomes more densely developed. Scientists with the CRU, GISS, and the NCDC have checked and corrected for such biases in various ways, but some critics remained unconvinced.

To address some of the concerns, a fourth group recently took a different approach to the problem. Richard Muller of the University of California (UC), Berkeley, and his daughter Elizabeth started the Berkeley Earth Surface Temperature project under the auspices of the nonprofit Novim Group in Santa Barbara, California; the project's collaborators include scientists from UC Berkeley, Lawrence Berkeley National Laboratory, and Oregon State University. The results were recently published,[4] although the work has been posted on the group's website (http://www.berkeleyearth.org) and publicly discussed for the past year.

The group's temperature estimates, done so far just for land surface temperatures, agree well with those from previous profiles. (See the figure on page 19.) The Berkeley group extended its analysis back to 1750, a century earlier than in other studies, although the sampling in the early period was poor. It might be useful to compare such data