

ons. There should be no charge carriers at that point but, nevertheless, the conductance there is nonzero. As Andrei explains, one can shoot in an electron and it will go through the graphene.

What happens to the conductance at the Dirac point when a magnetic field is applied? Will graphene remain metallic, or will it transition to an insulating state? Experiments have not provided a clear answer. Measurements by a Manchester team support theories of a conducting state<sup>7</sup> but later experiments by a Princeton group show evidence for a field-induced transition to an insulating state.<sup>8</sup> According to theory, which picture prevails depends on which symmetry is broken first. In one scenario, the Coulomb interactions in the presence of a strong enough field break the sublattice degeneracy, and the Dirac point transitions to an insulating state. In another scenario, the interactions break the spin degeneracy, and the state remains conducting. In the latter case, the material is insulating in the bulk; any conductance occurs in counterpropagating edge states. Even more possibilities exist in graphene bilayers because of the greater degree of degeneracy.

The new experiments on suspended graphene have weighed in on the side of the insulating state. Both saw resis-

tances jumping to values of 1–10 G $\Omega$  above certain critical values of the magnetic field. The critical field was as low as a few teslas, depending on the sample. Measurements on graphene bilayers also find an insulating transition, at an even lower critical field.<sup>6</sup>

Both Kim and Andrei find evidence that the insulating state near  $\nu = 0$  can obscure the FQHE that appears not far away at  $\nu = \frac{1}{2}$ . N. Phuan Ong of Princeton University thinks that the competition between those two effects will be one of the interesting questions to explore in future experiments.

Barbara Goss Levi

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## Gamma-ray telescopes show origins of cosmic rays

The long-held presumption that most cosmic rays are accelerated in supernova remnants has, until now, lacked convincing evidence.

The spectrum of cosmic-ray protons hitting the top of Earth's atmosphere falls smoothly with increasing energy  $E$  about like  $E^{-2.7}$  over six orders of magnitude from  $10^9$  eV to  $10^{15}$  eV. It has long been assumed that the protons (and the small contingent of heavier ions) that constitute 99% of the CR flux are accelerated to such high energies in the expanding shock waves of supernova (SN) remnants in our own galaxy. (For higher energies, one has to invoke much grander accelerators like actively accreting black holes in the nuclei of distant galaxies.)

The SN acceleration scheme, originally suggested by Enrico Fermi, involves cumulative acceleration of charged particles in repeated traversals of the remnant's shock front. From x-ray and  $\gamma$ -ray telescope data, it's known that electrons are indeed accelerated in nearby SN remnants. But electrons account for only about 1% of the CR flux. And until now,

convincing evidence of the presumed connection between supernovae and the acceleration of CR hadrons (protons and ions) has been lacking.

Because the trajectories of all but the most energetic charged particles are scrambled by the Milky Way's hodgepodge of magnetic fields, one learns nothing about the source of a CR of energy less than  $10^{19}$  eV from its arrival direction. A promising probe of CR sources, immune to magnetic scrambling, would be the  $\gamma$ s from the decays of neutral pions created in collisions between hadronic CRs and gas close to the acceleration source. And, indeed, the diffuse  $\gamma$  emission from the Milky Way's disk is attributed to such pion decays. But for observers inside the galaxy looking at the disk edge-on, it's been impossible to localize CR sources to regions rich in SN remnants.

Therefore in recent years astrophysicists have been hoping to verify the



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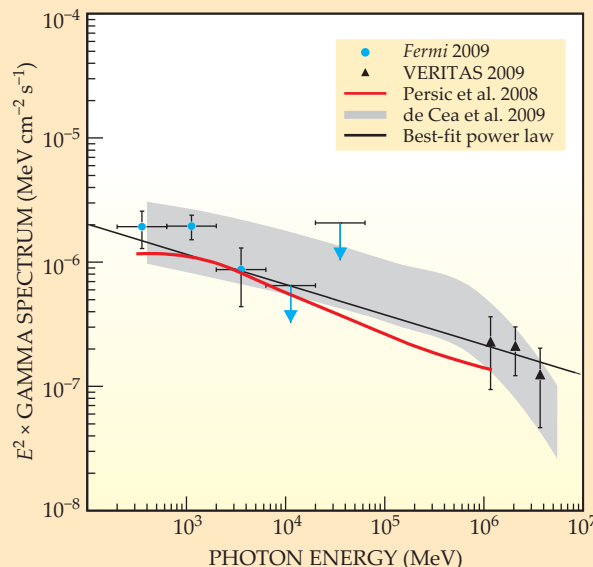
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CR–SN connection by looking for  $\gamma$  emission from nearby “starburst galaxies”—galaxies with regions of prodigious ongoing star formation at much higher rates than anything seen nowadays in the staid Milky Way. Because of their large populations of very massive, short-lived stars, starburst regions harbor extraordinary numbers of young SN remnants, and their local gas densities are very high. This combination would seem to make starburst galaxies promising places to look for pion-decay  $\gamma$ s from CR collisions. But that emission was predicted to be too faint for the previous generation of orbiting and ground-based  $\gamma$  telescopes to detect, even from the nearest starburst galaxies.

### ***Fermi*’s first year**

Now at last, a new generation of  $\gamma$  telescopes has revealed the predicted emission from two starburst galaxies—M82 and NGC 253—only about 12 million light-years away. Launched in June 2008, NASA’s *Fermi* Gamma-ray Space Telescope has far better sensitivity, angular resolution, and sky coverage than its predecessors. As *Fermi* sweeps the entire sky every three hours, it records the energies and directions of  $\gamma$ s from 20 MeV to 300 GeV.

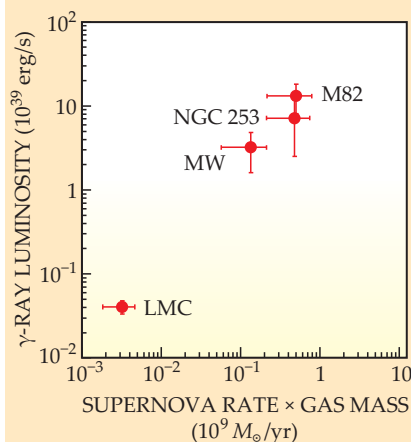
Over its first full year of observing,



**Figure 1. Gamma-ray spectrum of the starburst galaxy M82** measured by the *Fermi* and VERITAS telescopes<sup>1,2</sup> and compared with detailed theoretical predictions.<sup>4</sup> The simple power-law fit gives an energy dependence of  $E^{-2.2}$ . For clarity, the spectrum is multiplied in the plot by  $E^2$ . (Adapted from ref. 1.)

*Fermi* has recorded excesses over background of fewer than a thousand  $\gamma$ s arriving from the directions of M82 and NGC 253. Still, after careful analysis of backgrounds and the instrument’s angular resolution, a *Fermi* team coordinated by Keith Bechtol of SLAC has concluded that those small excesses constitute statistically robust detections of steady-state  $\gamma$  emission between 200 MeV and 20 GeV from the two nearest starburst galaxies.<sup>1</sup>

The same two galaxies have also been under scrutiny for TeV ( $10^{12}$  eV)  $\gamma$ s by Cherenkov-telescope arrays on the ground. Instead of detecting high-energy  $\gamma$ s directly, Cherenkov telescopes image the narrow cone of Cherenkov light reaching the ground from the shower of charged particles initiated when a TeV  $\gamma$  strikes the atmosphere (see PHYSICS TODAY, January 2005, page 19). Because such high-energy  $\gamma$ s are rare and the arrays have



**Figure 2. Gamma-ray luminosity** (for energies between 100 MeV and 5 GeV) versus supernova rate times total gas mass (in solar masses  $M_{\odot}$ ) for four galaxies: the Large Magellanic Cloud, the Milky Way, NGC 253, and M82. (Adapted from ref. 1.)

very narrow fields of view, the Cherenkov teams have had to make do with even skimpier statistics than the *Fermi* team.

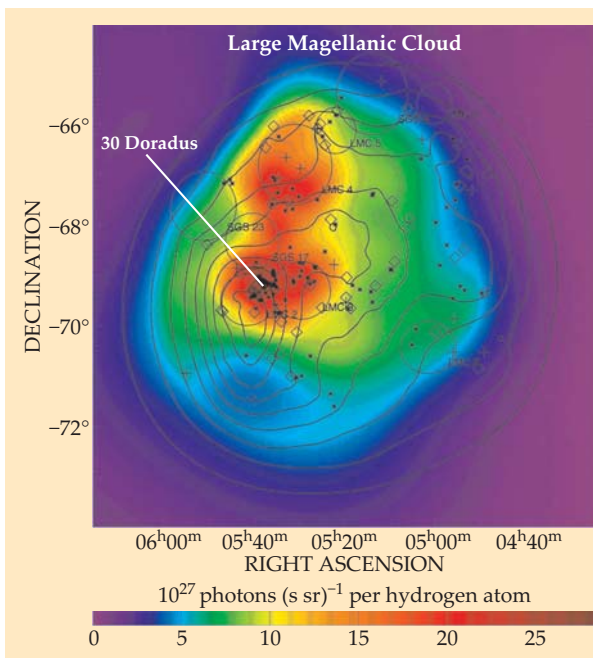
The two-year-old VERITAS array of four Cherenkov telescopes at the Whipple Observatory in Arizona has harvested an excess of only 91  $\gamma$ s above background in 140 hours of staring directly at M82. But that suffices, says team leader Wystan Benbow (Harvard-Smithsonian Center for Astrophysics), to provide a 5-standard-deviation detection of TeV  $\gamma$  emission from that galaxy in the northern sky.<sup>2</sup> In the southern sky, the HESS array in Namibia, three years older than VERITAS, has

been monitoring NGC 253, whose star-formation rate is only about half that of M82. Led by Werner Hofmann of the Max Planck Institute for Nuclear Physics in Heidelberg, the HESS team reports<sup>3</sup> a 5-standard-deviation signal of  $\gamma$  emission above 200 GeV from NGC 253.

### The first ever

The M82 and NGC 253 observations by *Fermi* and the Cherenkov arrays are the first detections ever made of steady-state  $\gamma$  emission from “ordinary” galaxies other than our own and the Large Magellanic Cloud (LMC), a close-in satellite of the Milky Way. “Ordinary” here means a galaxy without an active galactic nucleus (AGN)—a voraciously accreting supermassive black hole that powers gargantuan jets of charged particles and radiation. Until now, most of the many  $\gamma$ -luminous galaxies seen by *Fermi* and other detectors have been “blazars”—AGNs with jets that happen to be pointing toward us.

Figure 1 shows M82’s  $\gamma$  spectrum as measured over four orders of magnitude in energy by *Fermi* and VERITAS. The best power-law fit ( $E^{-2.2}$ ) makes good sense if one attributes most of the  $\gamma$  emission to the decay of pions produced in ambient-gas collisions of protons and ions accelerated in SN remnants. But one also wants to get the absolute normalization right. The detailed theoretical predictions<sup>4</sup> shown in the figure do that quite well. In addition to the pion-decay  $\gamma$ s, they also consider the lesser contributions of CR electrons to the  $\gamma$  flux by bremsstrahlung and Compton upscattering of ambient photons.



**Figure 3. Luminosity** map of the Large Magellanic Cloud from *Fermi* telescope data for  $\gamma$ s with energy above 100 MeV. Contour lines indicate density of hydrogen gas and colors indicate local  $\gamma$  emission per hydrogen gas atom. Symbols show already known stellar evidence of recent star formation: supernova remnants, Wolf-Rayet stars, and radio pulsars. All three indicators peak in the active star-forming region 30 Doradus. (Adapted from ref. 5.)

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The SN-remnant scenario implies that a galaxy's luminosity in  $\gamma$ s should scale roughly like the rate at which it produces supernovae times its total mass of gas. And indeed that's what is seen in figure 2, which compares the  $\gamma$  luminosities of the two starburst galaxies with those of the more quiescent Milky Way and LMC. The starburst galaxies exceed the Milky Way's meager SN output of a few per century by an order of magnitude, and the gas in their star-forming cores is extremely dense.

## Mapping the LMC

Small and staid though it may be, the LMC offers several important advan-

tages in the search for CR origins: It's very close by, we see it almost face-on, and it harbors a localized region of vigorous star formation—called 30 Doradus—more active than any neighborhood in the Milky Way. *Fermi*'s angular resolution is not nearly good enough to localize  $\gamma$  emission to known starburst regions within M82 and NGC 253 from a distance of 12 Mly. But it can do just that in the LMC, a mere 150 kly away.

Figure 3 is a map of the LMC's  $\gamma$  luminosity produced by a *Fermi* team led by Jürgen Knödseder of the Center for the Study of Space Radiation in Toulouse, France.<sup>5</sup> Contour lines indicate hydrogen gas density, symbols

mark the locations of known SN remnants and other stellar evidence of active star formation, and colors indicate  $\gamma$  luminosity divided by local gas density. All three indicators peak at 30 Doradus, a starburst region about 400 ly across.

That's what's expected if the CRs are produced in SN remnants and then show themselves by colliding with gas. Strictly speaking, the LMC map—and the starburst-galaxy results—tie the CRs only to star-forming regions and not specifically to SN remnants. It could therefore be that Wolf-Rayet stars—massive young stars in prolonged windy death throes—which also abound in such regions, play a role in CR accelera-

## physics update

These items, with supplementary material, first appeared at <http://www.physicstoday.org>.

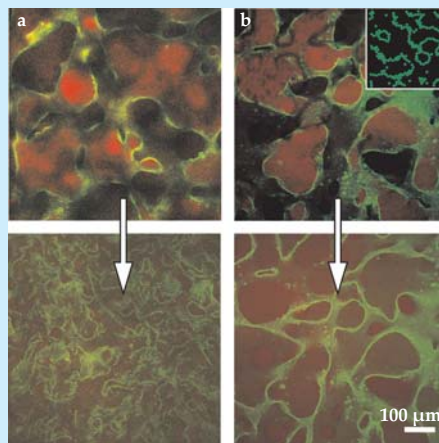
**A new look at friction.** We learn in introductory physics classes that the friction force is the product of a friction coefficient and the force normal to the interface. That relationship, embodied in the first of Guillaume Amontons's two laws of friction, has been superseded over the past 50 years by the recognition that the lateral friction or retention force is, in fact, proportional to the true contact area (see PHYSICS TODAY, September 1998, page 22). Amontons's law turns out to be a special but common case in which the contact area scales linearly with the normal force. In new measurements of liquid drops on surfaces, Rafael Tadmor and colleagues at Lamar University in Beaumont, Texas, observe the opposite behavior: a lowered lateral force despite a larger normal force and an increased contact area. Key to the observations was the ability to decouple the normal and lateral forces while monitoring the drop. To achieve that separation, the researchers mounted the sample at an adjustable angle in a horizontal centrifuge arm, shown here, that could be rotated about the vertical axis at a variable speed. A comounted camera wirelessly transmitted video to a nearby computer. Comparing the situation in which the drop of liquid was on top of a horizontal substrate to that in which the drop was hanging below a horizontal substrate, the team found that the hanging drop had the larger lateral retention force, despite a smaller contact area and a smaller normal force. That counterintuitive result agrees with theories that incorporate the effects of surface deformation and molecular reorientation. (R. Tadmor et al., *Phys. Rev. Lett.*, in press.) —RJF



**Arresting colloidal gel structures.** The tunable elasticity and porosity of colloidal gels lead to some interesting applications, among them tissue scaffolding and drug delivery. Conventionally, colloidal particles interact and assemble under entropic and electrostatic forces to form predictable structures. But greater control can be achieved from an approach developed by Paul Clegg, Michael Cates, and their collaborators at the University of Edinburgh in the UK. The researchers disperse silica particles in the single-phase region of two partially miscible solvents—

water and the organic base 2,6-lutidine. When the solution is heated above a critical temperature, the solvents separate and the particles become trapped at the liquid-liquid interfaces.

The bulky particle domains then jam together and arrest the solvent separation, forming a two-phase network the researchers call a *bijel*. But cool the solution and remix the solvents too soon and the distinct structure disappears, as shown in the two left images in which the colloids appear green, the water black, and the lutidine red. Now the researchers have discovered an approach to stabilize the *bijel* structure. When the phase-separated solution is allowed to sit for at least 24 hours before it is cooled, the *bijel* surprisingly keeps its shape, as shown in the two right images. (Movies accompany the online version of this item.) From Monte Carlo simulations, the researchers deduce how the resulting network of colloidal monolayers, or monogel, stays intact: The particles become compressed by capillary forces, remain attracted by van der Waals forces, and are kept from collapsing into each other by repulsive electrostatic forces. (E. Sanz et al., *Phys. Rev. Lett.*, in press.) —JNAM



**Musicality of speech changes with mood.** Loud, fast, rhythmic music is exciting. It mirrors aspects of human behavior—we are loud and active when excited. Likewise slow, soft, static music mimics how we behave when subdued. That congruence might explain why music affects us as it does. Also, melodies in a major key generally come across as happy; minor melodies are sad. But why those tonalities have their particular emotive effects is not clear. Now, Duke University neuroscientist Dale Purves, his graduate student Daniel Bowling, and colleagues report that qualities of major- or minor-key melodies also mirror human behavior—specifically, speech—according to the mood of the speaker. One of their analyses focuses on the intervals (tone pairs) implied by melodies. Major-key melodies emphasize the major-third interval, whose two notes have a frequency ratio of about 5:4. Minor-

tion. But stellar winds don't release enough energy to account for more than a small fraction of CRs. It's estimated that fully 10% of the kinetic energy released in SN explosions ends up in CRs.

The only surprise, says Knödlseder, is that the  $\gamma$  luminosity tracks the star formation so well. "It implies a mean diffusion length [ $L_d$ ] of only about 400 light-years from where the CR was created to where it collides and makes pions." Indirect evidence from the Milky Way disk's diffuse  $\gamma$  emission suggests a significantly longer  $L_d$ .

Because CR collisions with even the densest interstellar gas are few and far between,  $L_d$  depends much more on the

twists of local magnetic fields than on gas density. In fact, many hadronic CRs manage to leak out of their natal galaxies without ever making a pion. "So we have to imagine that the magnetic-fields near 30 Doradus are particularly intricate," says Knödlseder, "or rethink the evidence from the Milky Way's disk."

To the extent that hadronic CRs don't escape before making pions, a galaxy's  $\gamma$  luminosity becomes a calorimetric measure of its CR energy. The  $\gamma$  observations indicate that starburst cores of M82 and NGC 253 have CR energy densities a hundred times that at the Milky Way's center. "That difference reflects a similar disparity in supernova rates," says theo-

rist Massimo Persic (National Institute for Astrophysics, Trieste, Italy). "The correlation suggests that supernova remnants in very different environments share a common, perhaps universal, efficiency for accelerating cosmic rays."

**Bertram Schwarzschild**

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key melodies feature an interval, the minor third, with a 6:5 frequency ratio. How is that interval dichotomy mirrored in speech? The Duke team asked 20 subjects to read a word or short passage in an excited or subdued manner (see the texts in the online version of this item). They then analyzed the ratios of the two lowest—and strongest—frequencies of vocal-tract resonance associated with each vowel sound. The prevalence of major-third intervals (5:4 ratios) as compared with minor thirds (6:5) was much greater in excited than in subdued speech. Musically speaking, at least, our thrills are major; our disappointments, minor. (D. L. Bowling et al., *J. Acoust. Soc. Am.*, in press.) —SKB

**Putting a sound stop to convection.** The phenomenon of dynamic stabilization can be demonstrated with an inverted pendulum: If the pivot point vibrates fast enough and strongly enough, the pendulum aligns with the vibration direction and

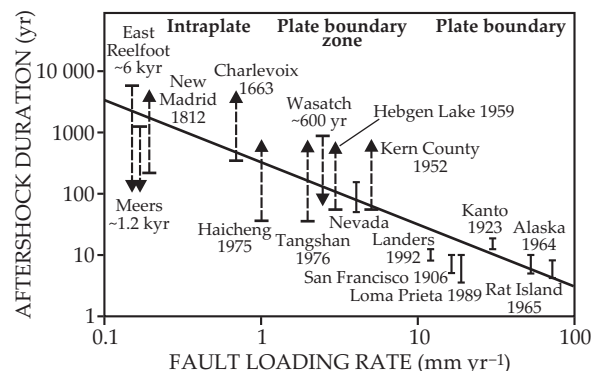


can stably stand upside down, even at an angle, seeming to defy gravity. Physicists Greg Swift and Scott Backhaus (Los Alamos National Laboratory) looked at an analogous situation with gas in a so-called pulse tube that has one end much hotter than the other. Colder gas is denser and therefore sinks below the hotter gas; a vertical tube with the cold end down is like an undisturbed pendulum with the heavy bob at the bottom. However, raise the cold

end above the hot end and convection sets in—the cold gas falls due to gravity and the hot gas rises in a natural convective flow. Such orientation-dependent effects are undesirable for cryogenic thermoacoustic pulse-tube refrigerators, like the commercial one shown here, in which the gas is used to transmit acoustic power but not heat. (For more on thermoacoustics, see *PHYSICS TODAY*, July 1995, page 22.) Swift and Backhaus found that suppression of convection when these refrigerators run at high enough frequency and amplitude is related to the well-understood stabilization of the inverted pendulum. Although

their experiments and theoretical analysis are beginning to unravel the essentially nonlinear physics at the core of the system, many mysteries remain, including the actual role of the oscillating pressure. (G. W. Swift, S. Backhaus, *J. Acoust. Soc. Am.* **126**, 2273, 2009.) —SGB

**Interpreting intracontinental earthquakes.** Our historical record of seismic activity is very short, by geological time scales. So extrapolating that record to predict future earthquakes can lead to nasty surprises, such as 2008's devastating earthquake in Sichuan, China, which occurred on a fault that had seen little recent activity. Large earthquakes are typically followed by aftershocks whose frequency decays to some background level of seismicity, following an empirical relation known as Omori's law. But determining the time scale of the decay and the baseline activity can be difficult. A new model by Seth Stein of Northwestern University and Mian Liu of the University of Missouri–Columbia posits an inverse relationship between the aftershock-sequence durations and the slip rates along faults. Large earthquakes are most common along the boundaries of tectonic plates, and the occurrences of aftershocks tend to decay quickly—within a decade or so—to a relatively high background. The relative plate motion at such boundaries can



be rapid, faster than 10 mm/yr. Continental interiors, far away from plate boundaries, deform much more slowly, typically less than 1 mm/yr. And thanks to that slower rate of fault loading, aftershocks can last hundreds of years or longer, as shown in the figure. Thus, warn the researchers, interpreting continental earthquakes as steady-state seismicity can overestimate the hazard in presently active areas and underestimate it elsewhere. (S. Stein, M. Liu, *Nature* **462**, 87, 2009.) —RJF ■