from an OPO would display greatly reduced entanglement or none at all.

Applications

Entangled light beams offer the ability to beat the quantum noise limit, set by the uncertainty principle, in measurements of intensity. The fluctuations of one beam can be subtracted from the measured intensity of the other, thereby eliminating most of the quantum component of the noise. Similarly, in measurements of the intensity of some spatial subset of a beam, it is likely that point-by-point entangled beams will be useful.

For example, in one commonly used technique for measuring the position of a laser beam, the beam is directed at a two-part photodiode, and each part measures the intensity of half the beam. When the measured intensities are equal, the center of the beam must lie on the dividing line between the two parts. Quantum intensity fluctuations of each half of the beam limit the precision of each photodiode measurement and thus the precision of the beam position. In 2003 an Australian–French collaboration presented a way of beating the quantum beam-positioning limit with a so-called "quantum laser pointer."[4] But those researchers created their beam by mixing two different spatial modes from two optical parametric amplifiers, close cousins of the OPO. Four-wave mixing could achieve the same end more easily.

Other applications may be found in the field of quantum information—that is, the use of quantum states for computation and communication. Quantum information protocols using discrete-variable systems may be more familiar (see, for example, the article by Andrew M. Steane and Wim van Dam, PHYSICS TODAY, February 2000, page 35), but continuous-variable protocols have been widely considered as well.[5] And for that, the JQI group's technique may prove advantageous. It produces, in effect, 100 independent sets of entangled quantum fluctuations as easily as an OPO can produce just one.

But the problem, once again, is in the detection. So far, the JQI researchers have looked at the entangled modes one at a time, but a quantum information application would require that different modes be manipulated and detected in parallel. The technology exists to separate them, but implementing it is a challenge.

Johanna Miller

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Very low-frequency radio waves drain Earth's inner radiation belt of satellite-killing electrons

A high-altitude nuclear explosion would swell the radiation belt and imperil the global positioning system and other satellites. VLF transmissions could forestall the damage.

Earth's magnetic field protects the planet from the Sun's hot, fast wind. Diverted by the field, the charged particles that make up the wind fly past Earth into interplanetary space. But plenty of them leak through, and some are trapped. Like mosquitoes on the inside of a mosquito net, trapped particles can be particularly irksome.

Indeed, the swarm of high-energy particles held in Earth's two radiation belts can damage, even destroy, the control systems, sensors, and solar cells of orbiting spacecraft. Although the slot between the radiation belts provides an orbital haven for satellites, orbits are typically chosen to maximize mission effectiveness, not to minimize radiation damage.

Besides, strong solar storms can change the size and location of the radiation belts. Spacecraft therefore require shielding not only against harsh prevailing conditions but also against severe rare storms.

No solar storm, however, has jolted Earth's inner radiation belt more than the nuclear test code-named Starfish Prime. On 9 July 1962, the US exploded a 1.4-megaton nuclear warhead 400 km above Johnston Atoll, a remote group of Pacific islands. In Hawaii, 1400 km away, Starfish Prime lit up the sky, knocked out street lights, triggered burglar alarms, and fused power lines (see figure 1).

Figure 1. The sky over Honolulu, Hawaii, glowed red on 9 July 1962 as x rays from the Starfish Prime nuclear test excited atomic oxygen in the atmosphere. The photograph comes from a 2004 congressional report on the threat to the US from an electromagnetic pulse attack.

Beta particles from the blast flooded the thin upper reaches of the atmosphere. Trapped by Earth's magnetic field, the high-energy particles swelled the inner radiation belt. Seven satellites, including *Telstar*, the first-ever communications satellite, were damaged or put out of action. The radiation took more than a decade to dissipate. Alarmed by Starfish Prime's unintended consequences, the nuclear powers banned testing in and above Earth's atmosphere in 1965.

But a hostile country with nuclear weapons and rocket launchers could emulate Starfish Prime and knock out the world's military and civilian satellites. If the country had no spacecraft of

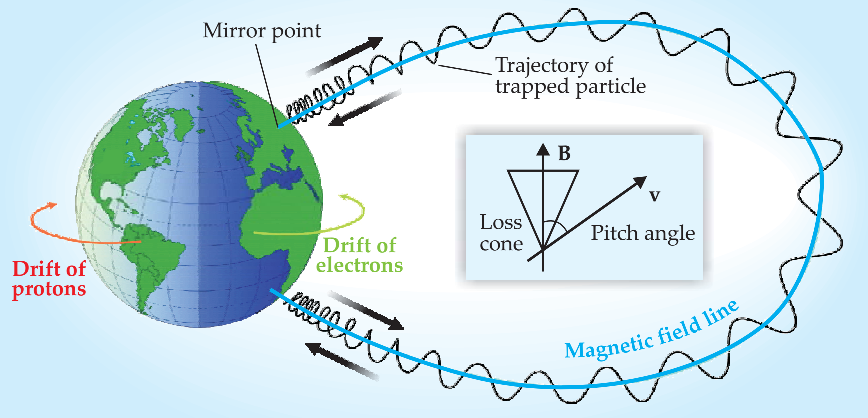

Figure 2. Electrons and protons trapped in Earth's inner radiation belt fly back and forth in helical trajectories between mirror points. At the same time, the particles' trajectories drift around Earth in a ring current. The idealized trajectory shown here would hold the particle indefinitely. But if at any point on the trajectory the particle's pitch angle shrinks and enters the loss cone, the mirror points could end up in the atmosphere, where the particle could scatter and escape its trap.

its own, the explosion would deliver a military advantage rather than a self-inflicted wound.

Defending against the threat is awkward. In principle, spacecraft could be shielded against the killer electrons. But each kilogram of shielding adds tens of thousands of dollars to the launch cost. Or, if weight is kept constant, extra shielding reduces the instrument payload. Fortunately, magnetospheric physics supports another potential defense: Very low-frequency radio waves.

Recent studies by a team from France and New Zealand have provided compelling evidence that VLF transmissions from a US Navy ground station in Australia are draining high-energy electrons from the inner radiation belt.[1] And in two years' time, the US Air Force plans to launch the *Demonstrations and Science Experiment* (DSX). From its orbit between the radiation belts, the satellite will help determine whether a spaced-based transmitter can perform what's known as RBR: radiation-belt remediation.

Pitch angle scattering

Earth's inner radiation belt is continuously supplied with high-energy electrons and protons. Most of the electrons come from the solar wind, whereas the protons arise from the decay of neutrons knocked out of atoms in the atmosphere by cosmic rays. If those electrons and protons reach altitudes between 0.1 and 1.5 Earth radii, the bounds of the inner radiation belt, they can be trapped.

What losses offset those gains? In the radiation belts, charged particles follow helical trajectories around magnetic field lines. As a charged particle nears a magnetic pole, the field lines converge and its helical trajectory becomes more compressed like a spring. Eventually, the particle will reverse course at a so-called mirror point and bounce back. Figure 2 illustrates the process.

Electrons trapped in the inner belt are so energetic they take about 0.1 s to make the round trip between reflections. The electrons also drift eastward, and the protons drift westward, thanks to the gradient and curvature of Earth's magnetic field. The trip around Earth takes about half an hour.

Whether an electron remains trapped depends on the altitude of the mirror points. The altitude depends, in turn, on the pitch angle, the angle the electron's trajectory makes with the field line.

If an electron finds itself at the magnetic equator with a pitch angle close to 90°, its motion around the field line will barely deviate from a circular orbit. Squeezed between two mirror points just above and below the magnetic equator, the electron will remain trapped far above the tropics.

The smaller an electron's pitch angle at the equator, the farther the electron will travel along a field line and the greater will be the separation between its mirror points. A trapped electron, like Starfish Prime's beta particles, could survive for years. But if the electron's pitch angle is nudged into the so-called loss cone, its new mirror points will drop into the atmosphere. When an electron arrives there, it may scatter off a neutral atom and fall out of its trap. The radiation belt will have lost an electron.

Collisions are too rare in the thin plasma of the radiation belt to scatter electrons and alter their pitch angles. Electrons are nudged into their loss cones by electromagnetic waves that resonate with the electrons' few-kilohertz cyclotron frequencies.

Several processes can perturb the ionosphere and launch waves, including atmospheric lightning. In 1998 Bob Abel of Olympic College in Bremerton, Washington, and Richard Thorne of UCLA evaluated the various sources of pitch angle scattering. According to their calculations, the most significant scatterer in the inner radiation belt is manmade: the powerful VLF transmissions used by the US Navy and other navies to communicate with submarines.[2]

Wisps of precipitation

Strong but patchy evidence of the effect of VLF transmissions has been accumulating for some time.[3,4] In 2004 the French National Center for Space Studies launched *Demeter*, a satellite whose payload and orbit turned out to be nearly perfect for clinching the case.

Demeter's circular orbit passes over Earth's geographical poles at an altitude of 710 km. Thanks to a careful choice of altitude and inclination, the orbit keeps pace with Earth's day–night terminator. If *Demeter* were visible from the ground, you could check a sundial and see the spacecraft fly overhead at the same two local times, 10:30 and 22:30, every day, wherever you were.

In *Demeter*'s payload is a detector called IDP that counts charged particles. The detector's combination of spectral resolution, field of view, and collecting area provides an unprecedented view of the electrons the spacecraft encounters as it skims the lower reaches of the inner radiation belt.

Because of its polar orbit, *Demeter* intercepts every magnetic field line, from the short loops that originate at low magnetic latitudes to the near-infinite loops that originate at the magnetic poles. How many electrons IDP counts at each location above Earth depends on where the local mirror point is in relation to the spacecraft.

Figure 3 shows a map of the 200-keV electron flux measured by IDP. If Earth's magnetic field were closer to a perfect dipole, IDP would measure the

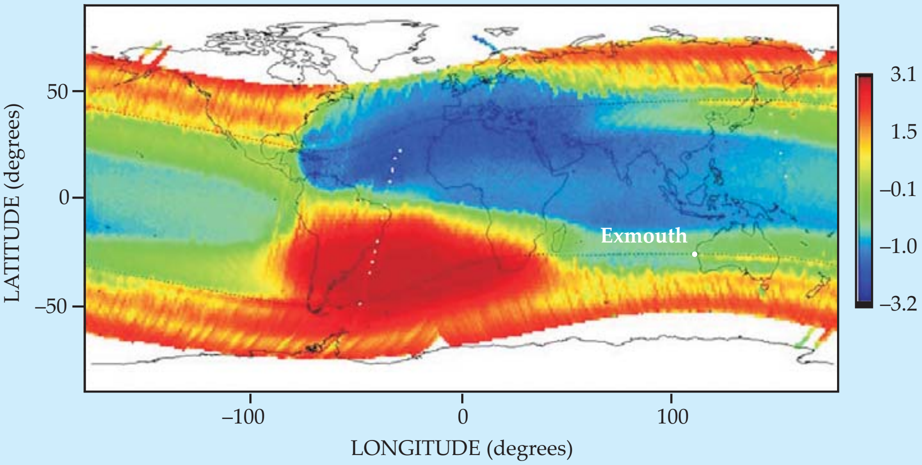

Figure 3. The flux of 200-keV electrons measured by the IDP detector aboard *Demeter* varies strongly with location. The map is made up of instantaneous count-rates gathered during thousands of orbits between October 2005 and October 2006. *Demeter* encountered the highest fluxes when it flew through the South Atlantic Anomaly and at latitudes around ±50°. The flux enhancement due to the very low-frequency transmitter at Exmouth, Western Australia, appears as two thin yellow trails: one originating above Exmouth, the other originating at the opposite end of the same field line. The scalebar is logarithmic and the units are electrons cm^{-2} sr^{-1} keV^{-1}. The blank regions at ±65° correspond to the auroral zones. (Adapted from ref. 1.)

highest 200-keV fluxes around geographical latitudes of ±50°. Those high-flux regions show up in the map as two wavy stripes, but they're far less conspicuous than the wide peak that spreads over the South Atlantic Ocean.

The peak, caused by a weak patch in Earth's magnetic field, is known as the South Atlantic Anomaly. Because the field is weak, mirror points in the SAA lie closer to Earth's surface and to *Demeter*'s path than they do outside the SAA. When *Demeter* flies through the SAA, IDP detects a surge of electrons. It detects a deficit of electrons when *Demeter* flies through the region in the Northern Hemisphere where those electrons would bounce back if they hadn't been lost in the SAA.

The principal investigator of *Demeter* is Michel Parrot of the Laboratory of Space Physics and Chemistry in Orléans, France. The principal investigator of IDP is Jean-André Sauvaud of the Center for the Study of Radiation in Space, in Toulouse, France. Two years ago they invited Craig Rodger of the University of Otago in Dunedin, New Zealand, to participate in *Demeter*'s guest investigator program.

Rodger's first challenge was to analyze the data. He assigned the task to his graduate student Rory Gamble. To assess the accuracy of their analysis software, Rodger and Gamble looked for the features they expected: the SAA, its Northern Hemisphere shadow, and the wavy, high-latitude stripes. They found them. But they also spotted a long, thin feature trailing eastward from the vicinity of Exmouth, on Australia's west coast.

Exmouth is the site of the Naval Communication Station Harold E. Holt. The station's 300-m-high antennas emit 1 MW of radiation at 19.8 kHz. It's the most powerful VLF transmitter in the Southern Hemisphere.

Low frequencies are favored for communicating with submarines because seawater, being a conductor, snuffs out higher frequencies within centimeters of the surface. A submarine can cruise meters below the surface and still pick up a VLF signal.

Another advantage of VLF signals is that the ionosphere reflects them, even at night when it's leakiest. The station at Exmouth can communicate with submarines spread over vast distances. In Dunedin, 5700 km away, Rodger and Gamble could easily tell when the Exmouth transmitter was on, even if they couldn't decode the secret signals.

The long, thin feature in electron flux indicated that trapped electrons were being drawn down to *Demeter*'s orbit. The feature, and its Northern Hemisphere reflection, appeared during 95% of Exmouth's nighttime transmissions. During daytime transmissions, too little VLF energy got through the ionosphere to cause a detectable effect. Sauvaud, Parrot, and their coworkers were also looking at IDP data for evidence of the same phenomena. The French and New Zealand researchers decided to work together.

Very low-frequency radiation is most effective at scattering electrons into their loss cones when its direction of propagation aligns with the magnetic field. That alignment seems unlikely, given that radiation from the Exmouth transmitter travels upward to meet field lines that are oriented 35° off vertical. But at Exmouth's magnetic latitude, tubes of cool plasma called whistler ducts are available to guide the radiation. A calculation matched the expected loss with the observations.

Having discovered the clear effect of the Exmouth transmitter, the French and New Zealand team looked for evidence that another VLF transmitter, in Hawaii, also caused electron loss. It didn't. At the Hawaiian station's lower magnetic latitude, whistler ducts are presumably too weak to provide much guidance.

Of course, the Exmouth station was not designed for radiation belt remediation. At best—that is, at night—only 1 kW of its 1 MW reaches the inner radiation belt. A space-based antenna orbiting above the ionosphere could be a more efficient remediator.

Efficient VLF transmitters need long antennas. Scheduled for launch after 2010, the air force's *DSX* will have an 80-m antenna, one-sixth the height of Exmouth's giant towers, and a 1-kW transmitter. Its aim is to explore the physics of injecting VLF radiation into space plasma. Effects on large-scale particle distributions, like those caused by Exmouth and seen by *Demeter*, are likely to be minimal.

Direct and deliberate intervention in Earth's radiation belts began remarkably early in the space age. In 1957, one year before James Van Allen and his collaborators discovered the radiation belts, Nicholas Christofilos proposed creating an artificial radiation belt. The dense layer of electrons, he theorized, could be useful as a defense against incoming missiles.

A year later, he got to test his idea—with a nuclear blast that created the world's first artificial aurora. At one thousandth the yield of Starfish Prime, it wouldn't have killed any satellites.

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X-ray outburst reveals a supernova before it explodes

Long predicted but never before seen, the x-ray harbinger let observers record the supernova's early light in unprecedented detail.

Core-collapse supernovae are attributed to a sequence of cataclysmic events presumed to follow from the exhaustion of the fusion fuel in the core of a star at least eight times more massive than the Sun: When the outward thermal and radiation pressure from exothermic nuclear fusion no longer balances the gravitational crush of the star's outer layers, the core suddenly collapses. The rebound from the collapse propels a shock wave outward through the star as a prelude to the eventual ejection of most of the star's material. Only a remnant neutron star—or a black hole—is left behind. The signature supernova light that first appears about a day later is eventually dominated, after weeks or months, by incandescence of the ejecta heated by the decay of radioactive nickel-56 created in the explosion.

The broad outlines of this scenario are supported by extensive observations of various spectroscopic classes of core-collapse supernovae at wavelengths ranging from radio to x ray. But until now, the data-taking has mostly begun only when the supernova had become optically bright, days after the core collapse. Such delay has left many details unclarified, progenitor stars unidentified, and theoretical presumptions unverified.

But now, by happy accident, Princeton University astronomers Alicia Soderberg and Edo Berger have observed an extremely luminous x-ray outburst manifesting the breakout of the rebound shock wave from the surface of a doomed progenitor star.[1] That serendipitous find allowed teams of observers to follow the ensuing supernova (labeled SN 2008D) almost continuously, in unprecedented detail, from just minutes after its core collapse to its radio afterglow months later.

Such a prompt supernova signal had been predicted 40 years ago by Stirling Colgate, but never seen until now. An x-ray outburst was seen in conjunction with a gamma-ray burst that heralded a 2006 supernova. But the character of that x-ray signal seems to have been peculiar to GRBs, which are generated by ultrarelativistic, highly collimated jets of ejecta produced by less than 1% of all core collapses.[2]

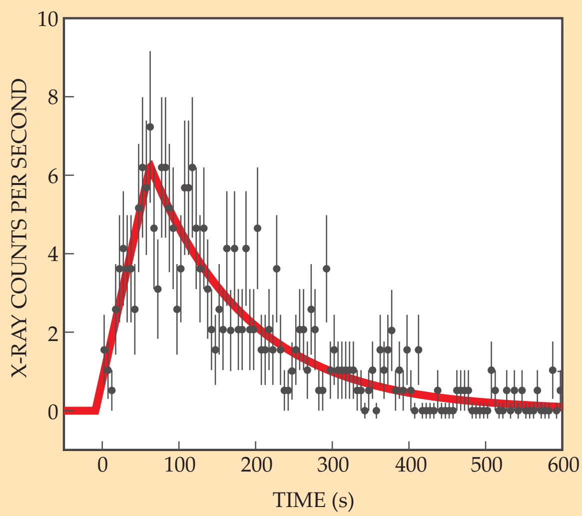

Figure 1. The abrupt rise and fall of the x-ray pulse serendipitously recorded on 9 January 2008 by the x-ray telescope aboard the *Swift* orbiter at the site of a supernova (SN 2008D) that would not become visible at optical wavelengths for another day or so. The curve is a fit with a linear rise followed by an exponential decay. (Adapted from ref. 1.)