by Govert Schilling

COSMIC POW

AIR SHOWER This artist's concept shows an example of the air shower of secondary particles that a high-energy cosmic ray creates when it hits Earth's atmosphere. The ground structure is one of the water tanks that serve as a Cherenkov-radiation detector for the Pierre Auger Observatory in western Argentina.

ER RANGERS

Scientists are deploying vast arrays on Earth to search for the origin of the most energetic particles in the universe.

In an uninhabited part of western China, between the arid Gobi Desert and the mountain peaks of the Tibetan Plateau, a novel radio observatory is taking shape. This spring, a few dozen weird-looking dipole antennas will start "listening" for extremely energetic neutrinos from outer space. Scientists will add thousands of additional units over the next five years, in an area 100 kilometers across. Eventually, the Giant Radio Array for Neutrino Detection (GRAND) will consist of 200,000 antennas in various parts of the world, covering a total area as large as Nebraska. The ultimate goal: solving the riddle of ultra-high-energy cosmic rays.

Cosmic rays are energetic particles — electrons, protons, heavier atomic nuclei, and their antiparticles — that zip through space at near-light speed. Most of them originate in the Sun, in supernova explosions and remnants, or in the vicinity of pulsars. But the origin of the most powerful cosmic rays is one of the oldest and largest mysteries in high-energy astrophysics. Since the charged particles are deflected by cosmic magnetic fields, their arrival directions do not tell you where they came from.

"But we expect that ultra-high-energy cosmic rays are accompanied by extremely energetic neutrinos," says GRAND project manager Charles Timmermans (Radboud University, the Netherlands), "and because neutrinos have no electrical charge, they point back to their source."

AIR SHOWER: A. CHANTELAUZE, S. STAFFI, L. BRET; BACKGROUND LINE TEXTURE: FUNKYPLAYER / SHUTTERSTOCK.COM

Austrian physicist Victor Hess discovered cosmic rays back in 1912, but studying them in detail has been frustratingly difficult. As soon as high-energy particles enter Earth's atmosphere, they collide with nitrogen and oxygen nuclei, producing an avalanche of rapidly interacting and decaying secondary particles. Only by capturing and measuring these fleeting *air showers* can scientists hope to learn more about the primary culprits. "From our data, we can derive the number of secondary particles at ground level, the arrival direction of the air shower, and the total energy," says Antonella Castellina (INFN Torino, Italy), co-spokesperson of the international Pierre Auger Observatory, currently the largest cosmic-ray observatory in the world.

For *ultra-high-energy cosmic rays* (UHECRs), an additional complicating factor is their sheer rarity. Particles with energies above 8×10^{18} electron volts (8 EeV, about 1% of the punch of a high-velocity baseball) only arrive at Earth at a rate of one per square kilometer per year. Little wonder that the origin of UHECRs is still pretty mysterious, even though the first one was detected almost 60 years ago, in 1962. "Finding the sources is by far the biggest challenge," says theorist Luis Anchordoqui (City University of New York).

Not that scientists are completely in the dark about the origin of UHECRs. In 2017, the Pierre Auger collaboration presented convincing evidence that they originate from beyond the Milky Way, as most researchers already suspected on theoretical grounds. Because of their high energy, UHECRs experience a smaller deflection by magnetic fields than lower-energy cosmic rays — in general, less than 25°. Looking at the arrival directions of more than 30,000 of these "baseball particles" over a period of 12 years, scientists found that about 6.5% more UHECRs are coming from one half of the sky than from the opposite half. This anisotropy is not aligned with the galactic center, as you might expect in the case of a galactic origin, but with the slightly lopsided distribution of external galaxies within 150 million light-years or so.

Energetic air-shower particles pass through the tanks at velocities that are higher than the speed of light in water.

One year later, the team announced a possible association of even more energetic UHECRs (above 4×10^{19} eV) with relatively nearby starburst galaxies (galaxies with an exceptionally high star-formation rate) — in particular, NGC 4945 in the constellation Centaurus, NGC 253 (Sculptor), M83 (Hydra), and NGC 1068 (Cetus). "At present, it's just a strong hint," says Castellina — the statistical significance of the correlation isn't yet large enough to claim a discovery. More data are crucial to obtain a higher degree of confidence, she explains. "We keep observing."

A Sea of Water Tanks

Located in the Pampa Amarilla northeast of the Argentinian town of Malargüe, the Pierre Auger Observatory (named after the French physicist who pioneered air-shower observations) covers an area of 3,000 square kilometers — about the size of Rhode Island. Its some 1,660 surface detectors, spaced about a mile apart, consist of tanks that look like giant Jacuzzis, each holding 12,000 liters of purified water. Sensitive silicon photomultipliers register the faint Cherenkov radiation produced when energetic air-shower particles pass through the tanks at velocities that are higher than the speed of light in water — a

▶ **TEAM EFFORT** Outreach coordinator Greg Snow (1954–2019) stands with the final tank of the 1,600 originally deployed, signed by collaboration members. Later, the array team installed additional tanks, part of a more densely spaced section to enable detections at lower energies.

▼ **PIERRE AUGER** Long-distance view of a line of the observatory's Cherenkov water tanks (small white structures).

PIERRE AUGER OBSERVATORY: LUKAS NELLEN / PIERRE AUGER OBSERVATORY / CC BY-SA 2.0; SIGNED TANK: PIERRE AUGER COLLABORATION / CC BY-SA 2.0

phenomenon comparable to the sonic boom of a fighter jet breaking the sound barrier.

Meanwhile, from four locations around the perimeter of the observatory, a total of 27 wide-field telescopes with 3.6-meter segmented mirrors keep an eye on the sky above the pampa, looking for the ultraviolet fluorescence caused by the interaction of the air-shower particles with atmospheric nitrogen atoms. The Pierre Auger Observatory started operating in early 2004 while still under construction and was officially inaugurated in November 2008. "Our stations have recorded many millions of signals to date," says Castellina. "At energies above 3×10^{18} eV, where our detector is fully efficient, the number of extensive air showers is on the order of 15,000 per year."

Using data from the surface detectors, scientists can reconstruct the spatial orientation and the spread of the air shower, as well as the number of secondary particles that reach Earth's surface. From the UV observations of the fluorescence detectors, they estimate the total energy of the primary cosmic-ray particle, while the altitude at which the fluorescence trail reaches its peak brightness indicates the incoming particle's nature: Protons and electrons penetrate to lower altitudes than heavier nuclei with the same energy.

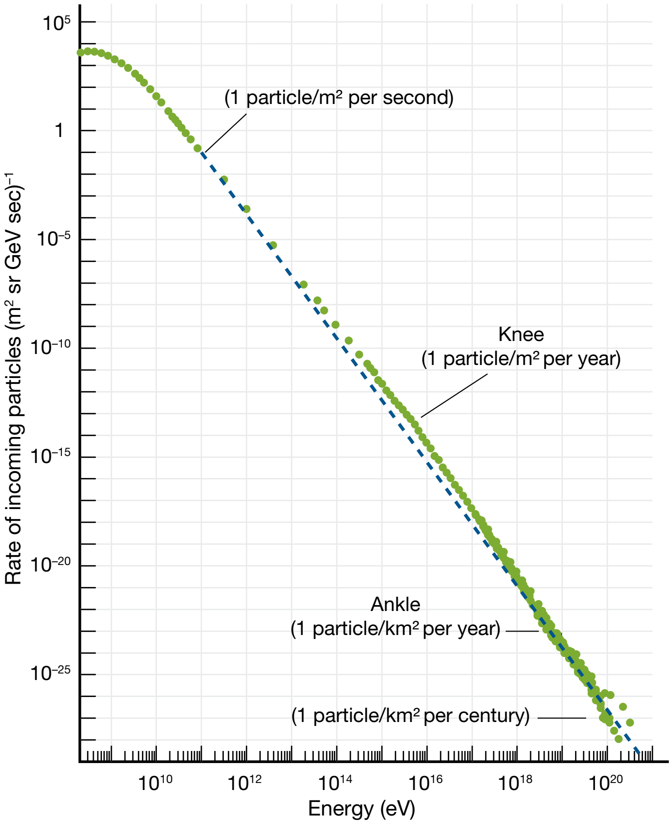
Unfortunately, the fluorescence detectors can only operate during cloudless and moonless nights — about 15% of the time. That's where radio observations come in — they don't care about weather or daylight. As Castellina explains, there are two ways in which particle showers produce radio waves. The more prominent source is electrons and positrons (anti-electrons) produced by the decay of secondary cosmic-ray particles: When they are deflected by Earth's magnetic field, they emit radio pulses. But relativistic charged particles moving through the atmosphere also emit a cone of radio waves known as Askaryan radiation, after the Soviet-Armenian physicist who predicted the effect in 1962.

Test observations with the Auger Engineering Radio Array (AERA) — a network of more than 150 simple dipole radio antennas — have demonstrated that astronomers can also use radio detections to estimate the energy of primary cosmic rays. That's why engineers are now installing 1,660 radio antennas (one at every surface detector) as part of an ongoing upgrade of the observatory, known as AugerPrime. The upgrade also includes 1,660 flat particle detectors known as *scintillators*, each with an active surface area of 3.2 by 1.2 meters, that will help characterize the secondary particles in the air showers. These in turn provide more information on the nature of the primaries. The AugerPrime deployment has been delayed by the COVID-19 pandemic, but it should be completed in 2022.

GREGG DINDERMAN / S&T, SOURCE: WILLIAM HANLON / UNIV. OF UTAH

Hotspot Connection

In the Northern Hemisphere, the smaller Telescope Array project in western Utah is also undergoing an upgrade, quadrupling its current dimensions (some 750 square kilometers) to a size comparable to Pierre Auger's. However, the Telescope Array lacks Cherenkov water tanks; it just consists of hundreds of scintillators and three fluorescence detector stations.



▲ **COSMIC RAYS** The flux of cosmic rays bombarding Earth as a function of their energy per particle. Scientists think those above the "knee" come from within the Milky Way, while those of higher energies come from outside our galaxy. Ultra-high-energy cosmic rays lie around the "ankle" or beyond.

"It's not easy to compare the results of the Pierre Auger Observatory and the Telescope Array," says theorist Anchordoqui. "They are different experiments with different properties, and they use different analysis techniques." Still, scientists from both projects are working together to combine the two data sets.

Interestingly, the Telescope Array has detected a 40°-wide UHECR hotspot in the sky centered in Ursa Major, possibly associated with the starburst galaxy M82. If confirmed, it would support the possible link between UHECRs and nearby starburst galaxies found by the Pierre Auger collaboration. "Everything seems to be closing together," Anchordoqui says, "although it's still unclear what makes these handful of starburst galaxies so special. There are many dozens of other galaxies at similar distances that do not appear to contribute as strongly to the observed UHECR flux."

Central black holes can't be the answer, he adds, since they are found in almost every galaxy. Anchordoqui's favorite explanation is galactic superwinds — powerful gaseous outflows that result from huge numbers of supernova explosions. Indeed, M82 and NGC 253 show clear evidence of such superwinds. Shock fronts in the outflows could accelerate particles to ultra-high energies.

Solving the mystery of ultra-high-energy cosmic rays has been hampered by a somewhat unexpected property of these baseball particles: At higher energies, they contain a higher proportion of heavier nuclei. Pierre Auger data indicate that the proportion of protons (hydrogen nuclei) eventually falls off to some 20%; most of the UHECRs are nuclei of carbon, nitrogen, oxygen, silicon, or even iron. Because of their larger (positive) electrical charge, these nuclei are easier to accelerate to near-light speed, even though they are more massive. But for the same reason, they are also easier for magnetic fields to deflect, making it harder to precisely trace them back to their source.

Follow the Fluorescence

To firm up the UHECR/starburst galaxy correlation, astrophysicist Angela Olinto (University of Chicago) says researchers need to gather more data at the highest possible energies. “You need to be more sensitive, which means larger. However, 3,000 square kilometers is already quite a lot, so how do you get there? The answer is: Go into space.” While Pierre Auger and the Telescope Array can only monitor a relatively small part of the atmosphere, an orbiting ultraviolet space telescope could survey huge portions of Earth’s nightside for the fluorescence trails produced by air showers.

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The idea was first proposed some 40 years ago by American physicist John Linsley, who discovered the first UHECR in 1962. However, NASA’s plan for an Orbiting Wide-angle Light-collectors mission (OWL) failed to materialize, and a competing European/Japanese mission was likewise aborted after many delays and financial setbacks. At present, the only operational instrument looking for fluorescence trails from space is a small UV telescope known as Mini-EUSO (for Extreme Universe Space Observatory), which was installed at the International Space Station in August 2019.

Olinto is the principal investigator of a major new initiative called POEMMA, for Probe of Extreme Multi-Messenger Astrophysics. Her team first proposed the billion-dollar

JOHN MATTHEWS / UNIVERSITY OF UTAH

▲ **TELESCOPE ARRAY** This solar-powered scintillation detector measures the strength and direction of air-shower particles created by incoming cosmic rays. The setup is how it appeared in 2014, when the collaboration announced its hotspot detection.

space mission for the study of ultra-high-energy cosmic rays to NASA in 2016. In 2019, the researchers submitted a detailed design study for review by the 2020 Decadal Survey on Astronomy and Astrophysics of the National Academies, which is expected to report its recommendations this spring. If the proposal receives a high ranking and NASA gives the green light, POEMMA could launch by the end of the decade, according to Olinto.

POEMMA consists of two identical spacecraft circling Earth in the same orbit, some 300 kilometers behind each other. The stereo vision of its two eyes — 4-meter wide-angle telescopes equipped with sensitive ultraviolet cameras — would enable a full 3D reconstruction of any fluorescence trail in the atmosphere. "What we need is a lot of events with directions," says Olinto, "and over time, POEMMA will observe large swaths of the Earth's nightside. Within five years or so, it should be possible to map the sources of UHECRs."

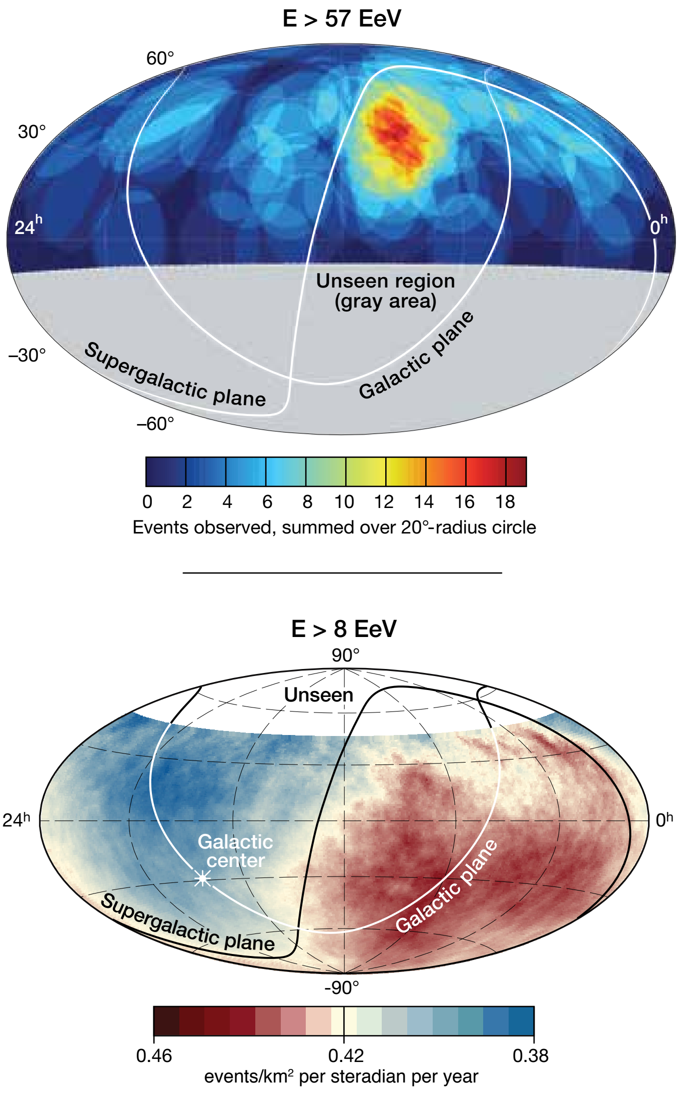
Geography to the Rescue

By then, however, the UHECR riddle may have been solved by GRAND, the prototype of which is now taking shape in western China. Just like the new radio antennas of Pierre Auger, GRAND will also detect air showers produced by cosmic-ray particles, but its ultimate goal is to hunt for extremely energetic neutrinos. "These high-energy neutrinos have never been observed before," says Timmermans, "but we're very confident they must exist, although they're apparently quite rare."

No matter how cosmic-ray particles are accelerated to UHECR levels, explains Timmermans, you expect them to incidentally crash into atomic nuclei in the ambient interstellar medium — probably close to their source, where densities are much higher than in intergalactic space. Through $E = mc^2$, the sheer energy of these collisions is converted into a wide variety of new particles, including uncharged neutrinos. According to theoretical calculations, these neutrinos carry some 5% of the energy of the original cosmic-ray particle. In other words, a burst of UHECRs of 10^{20} electron volts should be accompanied by neutrinos of a few times 10^{18} eV.

Because magnetic fields don't deflect neutrinos, any high-energy neutrino arriving here on Earth points directly back to its origin. Unfortunately, not all of the particles will come from pinpoint sources: UHECRs can also create high-energy neutrinos by interacting with the cosmic background radiation, which is all over the sky. But any neutrinos produced together with the UHECRs will betray where the most energetic particles in the universe originate, with a precision of better than half a degree. "It would be great to really discover one or more discrete sources on the sky," says astroparticle physicist Sijbrand de Jong (Radboud University, The Netherlands), who pioneered the Auger radio observations and is also a member of the GRAND collaboration.

But how do you detect these high-energy neutrinos? That's where the Tibetan Plateau mountains come in. Somewhat counterintuitively, the most energetic neutrinos are more likely to interact with normal matter than their lower-energy siblings — because of their higher energy, they have a larger *cross section*, as physicists say. While low-energy neutrinos easily pass through a planet like Earth, the particles that GRAND is after have trouble penetrating a few tens of kilometers of solid rock. So if their source is low above the horizon — hidden from view by the mountains, as seen from GRAND — they will enter the mountains from behind and most likely interact with a nucleus somewhere in the rock. These interactions produce short-lived particles that may emerge from the near side of the mountain range, in full view of the GRAND radio antennas.



▲ **ORIGIN HINTS** In the Northern Hemisphere, the Telescope Array has detected more extremely energetic cosmic rays coming from a hotspot centered in Ursa Major *(top)*. Operating in the Southern Hemisphere, the Pierre Auger Observatory has seen more cosmic rays (including those of slightly lesser energy) coming from one half of the sky than the other *(bottom)*. Unfortunately, the two experiments see different parts of the sky and have different energy cutoffs, so it's difficult to compare their data. (The supergalactic plane is the plane of nearby galaxy clusters.)

TELESCOPE ARRAY HOTSPOT: R. U. ABBASI ET AL. / *ASTROPHYSICAL JOURNAL LETTERS* 2014 (790:L21); COSMIC DIPOLE: PIERRE AUGER COLLABORATION

If the incoming high-energy neutrino is an electron neutrino, the interaction produces an electron, which will never leave the mountain at all. In the case of a muon neutrino, a negatively charged muon is produced — the heavier cousin of the electron. Such energetic muons will emerge from the mountain and zip through the atmosphere undetected.

However, in the case of a tau neutrino, the interaction yields an even more massive tau lepton, or tauon. "Tau leptons have a lifetime of about a trillionth of a second," says de Jong, "but because of a relativistic effect known as *time dilation*, they can cover tens of kilometers before they decay into a shower of other particles." These other particles include electrons and positrons, which can be detected by the radio waves they emit when deflected by Earth's magnetic field.

So here's the idea. Like the AERA array in Argentina, GRAND will be able to detect the radio emission of all kinds of air showers. But if the shower is a "horizontal" one, coming from the direction of the Tibetan Plateau mountains, it cannot be due to an incoming cosmic-ray particle or a high-energy gamma ray: Charged particles and photons are not able to penetrate kilometers of rock. Instead, the culprit must be a neutrino, and at least some of the highest-energy neutrinos are expected to be generated in the same extragalactic sources that also produce ultra-high-energy cosmic rays.

GRAND will observe at low radio frequencies between 50 and 200 megahertz, using thousands of antennas separated by about 1 kilometer. Each station consists of three butterfly-shaped dipoles at right angles to each other, to also measure the polarization of the radio waves. And if the first, 10,000-square-kilometer version in China (GRAND10K) is successful, the plan is to expand the observatory to a whopping 200,000 square kilometers all across the globe. Adding similar fields elsewhere in the world will increase the sky coverage and the detection rate. "All you need is a radio-quiet region with nearby mountains," quips de Jong.

Argentina, with the Andes range along its western border, is an obvious choice, according to Timmermans, but his team is also eyeing northern Canada (close to the Rocky Moun-

CHARLES TIMMERMANS

tains) and Russia (east of the Ural range). “The Transantarctic Mountains would also work,” he says, “although deploying tens of thousands of radio antennas in Antarctica is going to be expensive.” Currently, the full-scale version of GRAND is budgeted at somewhere between $150 and $200 million — a lot of money for a ground-based facility, but significantly cheaper than a space mission like POEMMA.

Timmermans and de Jong are very hopeful that GRAND eventually will detect discrete sources of extremely high-energy neutrinos. If they do, it would be bad news for Anchordoqui’s superwind model. If UHECRs are accelerated in galactic superwinds, as he believes, the acceleration takes place in the tenuous halos of galaxies, where densities are probably too low to produce large numbers of high-energy neutrinos. “If GRAND finds discrete sources of high-energy neutrinos, the superwind scenario cannot be correct,” Anchordoqui says, “and UHECRs must be accelerated in the cores of galaxies.” In that case, scientists will have to revisit the question of why only some galaxies produce UHECRs.

But Anchordoqui isn’t convinced that GRAND will have a serious impact on revealing the sources of UHECRs. “My personal opinion is that the radio technique is not yet mature enough,” he says, “so I think AugerPrime is more likely to make the big discovery.”

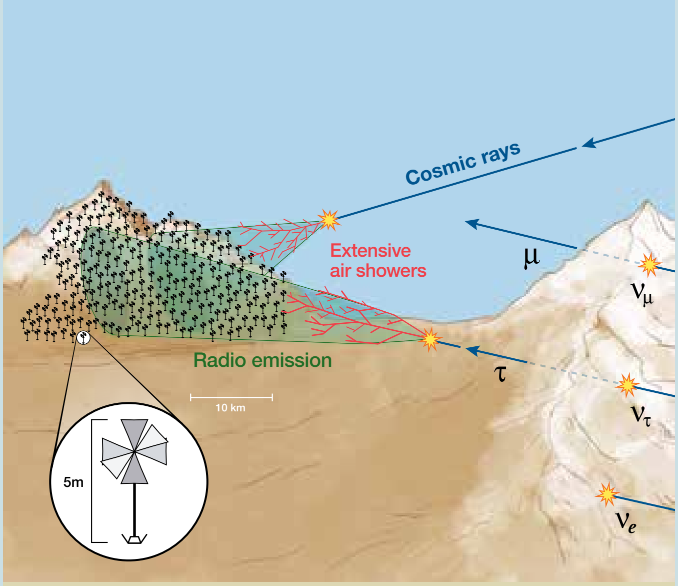
According to Timmermans, however, that won’t happen before 2025, and it will depend on how long it takes for the individual detections to add up into clear, localized signals. “If AugerPrime hasn’t found discrete sources by 2030,” he says, “I believe that GRAND will have the best chances of achieving the breakthrough.”

Meanwhile, if the POEMMA mission gets the green light, its observations may well yield an independent answer by the mid-2030s. One way or the other, the elusive energetic particles probably won’t stay a riddle for much longer.

Contributing Editor **GOVERT SCHILLING** is a science writer who lives in The Netherlands. He has written dozens of books and is currently writing a book on dark matter.

GRAND SITE: CHARLES TIMMERMANS; HOW GRAND WORKS: GRAND COLLABORATION

◀ **GRAND FUTURE** *Far left:* This windswept site in western China is the home of the growing Giant Radio Array for Neutrino Detection. Standing at the site are Xiang-Ping Wu and Huang Yan (National Astronomical Observatories of China). *Near left:* The setup for site survey operations. Scientists used easily moved antennas to measure background noise.



▲ **GRAND** The Giant Radio Array for Neutrino Detection will eventually use thousands of radio antennas to detect the signal of cosmic rays and tau neutrinos. Unlike muon or electron neutrinos, tau neutrinos will interact with atoms in neighboring mountains to create a detectable particle shower. The antennas have a triple bow-tie design, with three perpendicular arms. (Note that the mountain-facing slope the antennas are deployed on will be gentler than shown here.)