Moonshine and Glue

A Thirteen-Unit Guide to the Extreme Edge of Astrophysics

OLIVER MORTON

1. Nanoseconds

It's around seven o'clock on a Saturday evening in the spring of 2002, and in the pedestal lab we are in urgent need of a few more nanoseconds. The team—two NASA staff researchers, two university professors, a graduate student, and for this weekend only, a writer—is looking for them in closets and in toolchests. We're searching the shelves behind the equipment racks that line the sloping and windowless outer wall of this strange, doughnut-shaped room. As we look, the clock on the wall ticks on—and so does the clockwork our laboratory is part of. Like a cog geared to the celestial spheres, the giant radio dish that is mounted on top of the conical pedestal where we are working is turning remorselessly to the west as it receives transmissions from a spacecraft orbiting Mars. Soon Mars will set, and the dish will be turned over to the team in the pedestal lab. Their Goldstone Lunar Ultra-high-energy-neutrino Experiment, or GLUE, will get one of its infrequently scheduled opportunities to detect the most energetic particles physicists have ever looked for. And right now, an acute shortage of nanoseconds means GLUE isn't ready to take advantage of the opportunity.

If the particles GLUE is looking for exist at all—there are no guarantees—they are extremely rare. You could wait for centuries before one

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actually passed through the seventy-meter dish above us, and you'd probably miss it even then. But GLUE isn't trying to capture its prey locally. It's trying to detect the particles hitting the moon. The five people in the pedestal lab with me have lashed together one of the largest and best radio telescopes in the world and a few trillion tons of moon rock in order to produce a makeshift particle detector 400,000 kilometers long. Their undertaking encompasses a bewildering range of scales—scales measured in strange units such as zettavolts and megaparsecs.

But for all its cosmic scope, this is not the sort of "big science" that employs standing armies of technicians working on bespoke machinery. It is a cobbled-together parasite, entirely dependent on the ability of the five people in the lab to anticipate problems and improvise solutions as the clock ticks away. This afternoon's crisis is the recently diagnosed shortage of nanoseconds. If we can't find enough of them, tonight's five hours of precious observing time will be wasted, just as last night's were, because of noisy neighbors.

Walk out of the pedestal lab and the noisy neighbors are far from apparent: you are in the middle of California's Mojave Desert, among low hills sparsely carpeted with creosote bushes. In the late 1950s, when the Jet Propulsion Laboratory (JPL), a research institute in Pasadena run by Caltech for the federal government, needed somewhere from which to track and monitor the spacecraft it was beginning to build, a site near the Goldstone dry lake bed in the Mojave Desert was chosen. It was far from radio transmitters and power lines and other sources of interference, but still within a few hours' drive of JPL. The Goldstone Deep Space Communications Complex now hosts a twenty-kilometer daisy chain of nine large dishes; it and its sister facilities in Spain and Australia make up NASA's Deep Space Network. While the network's main purpose is to keep tabs on spacecraft all across the solar system, some scraps of time on the system are occasionally made available to other projects, such as radio astronomy and the study of nearby asteroids and GLUE.

Unfortunately for GLUE, in 1980 the military base on which Goldstone is located, Fort Irwin, became the Army's National Training Center, the site of the hardest-fought war games in the world: "World Class Training for the World's Best Army," as the sign at the fort's front gate puts it. None of this activity can be seen from Goldstone. But when digitized battalions slug it out with all the tools of modern warfare, radio, radar, and electronic warfare emissions fly as freely around Fort Irwin as bullets in a battle. For people listening to signals from distant spacecraft on prearranged frequency bands, this noise is not too much of a problem. But GLUE is listening for short broadband bursts of radio given off at random, and radio interference from the military next door is its biggest headache.

To minimize the difficulty, the GLUE team has developed an early-warning system. In addition to monitoring the moon's surface with two of

Goldstone's main antennae, it uses a separate receiver to monitor radio noise from nearby. Because of the way the experiment is wired up, the signals from this little local receiver arrive at the pedestal lab a bit more than a millionth of a second—a microsecond—before the signals from the main antenna do. This is because the signals from the big dish take a detour via a control room in a neighboring building. The spare microsecond is the time taken by that detour, and the delay is quite handy. It means that a salvo of noise from the war games picked up directly by the little local receiver can be used to "set a veto" in the circuits dealing with the signals coming in from the big dish. The veto is a 2.5-microsecond moratorium on taking data. When the burst of noise finally turns up in the signals from the big dish, the veto will be in place, and the noise will be ignored rather than treated as data.

It's a clever system. But looking at Friday night's data on Saturday afternoon—it's not possible to look at the results in detail while they're coming in—the GLUE team realized that the war game that was going on in the silent darkness outside was producing radio noise that the system couldn't handle. GLUE's graduate student, Dawn Williams, from UCLA, and Kurt Liewer, one of the two people from NASA, diagnosed the problem. The machine reacting to local signals with vetoes—a laboratory workhorse called a 222 gate generator—is unable to do more than one thing at a time. If a second burst of noise comes in on the little local antenna during a veto, there will be no corresponding second veto. And so, since the first veto will be over by the time the second burst comes through the cables from the big dish, the second burst of noise will make its way into the experiment's data. On Friday night, there were a lot of bursts within microseconds of one another, and the inability to set off vetoes in quick succession meant that the experiment was not able to cover its ears to all of them. As a result, the arduous 2:00 A.M. to 8:00 A.M. observing run was more or less worthless.

So today the team is trying to improve the system. It turns out that there are some vetoing machines around that are more flexible than the 222, machines that can set a second veto while a first one is going on. But these vetoes last only half a microsecond—500 nanoseconds. Since the warning signal arrives a full microsecond before the main signal, a half-microsecond veto is not long enough—it would be over before the burst of noise turned up in the main signal. One way to sort this problem out is to arrange things so that the gap between the warning signal and the burst of noise in the main signal is shorter. That means we need to delay the warning signal by a millionth of a second or so.

In a vacuum, the speed of light is about 300 million meters a second. So in a billionth of a second—one nanosecond—light travels about 30 centimeters, or 1.17 inches. In anything other than a vacuum, light and its electromagnetic relatives such as radio waves travel more slowly. Radio waves in one of GLUE's cables travel at about two-thirds of the speed of light in a vacuum, which means that a nanosecond is about 20 centimeters of cable. To delay the warning signal for a microsecond—a thousand nanoseconds—we need to send it down a cable about 100 meters long with a device at the far end that will bounce the signals back when they reach it.

A pretty thorough search of the pedestal lab doesn't turn up anything like enough nanoseconds of spare cable. So Liewer and his NASA colleague Chuck Naudet head off to scavenge some more from a dish at the other end of the lake. While they are gone, the two professors, David Saltzberg, of UCLA, and Peter Gorham, of the University of Hawaii, the man who thought up GLUE, try an alternative solution, wiring together a series of separate veto systems, quite amused by the idea that they could have the whole problem sorted out this way before Liewer and Naudet come back. This attempt comes to nothing, though—they forgot about a crucial diode, Liewer later points out with a touch of relish—so when Naudet turns up with arms full of heavy tangled cable, we all start untwisting and untangling it, sorting it into neat coils and finding the right little gadgets to link those coils together. (The cable comes in a bewildering array of five different standards; everyone concerned seems to have a vast toolbox mostly filled with connectors capable of bridging all the different gaps.) By the time we have five good coils of the stuff, one of the oscilloscopes in the lab's equipment racks shows that signals sent down the cable are coming back with a healthy 1.16 microseconds of delay. Six happy smiles. The nanoseconds embodied in those five coils of cable mean that when the great dish above us leans over to the east to catch the rising moon, GLUE will be able to ignore the shouts and alarms of nearby war games, the better to listen for the elusive echoes of zettavolt neutrinos.

2. ZETTAVOLTS

Neutrinos are subatomic particles whose activities—and indeed existence—are of no practical concern to anyone. Although the universe is crammed with neutrinos—the nuclear reactions within stars produce them in unfathomable abundance—most of them interact with atoms extraordinarily rarely. There are billions of neutrinos from the sun passing through your body every second as you read this, not doing you any harm at all; I can assert this without knowing whether you are reading by day or night, since these low-energy solar neutrinos pass through the solid earth beneath as easily as through the empty space above.

These phantoms have recently been shown to have a mass—the question was open for a long time—but it's a very small one. In particle physics, mass is measured in electron volts. The electron volt is in fact a unit of energy—the energy gained by an electron accelerated across a potential difference of one volt—but since energy can be translated through the simple use of $E=mc^2$, it works for mass, too. The mass of an electron, by far the lightest of the particles in atoms, is 512,000eV; a neutrino from the sun, by measly contrast, weighs at most 1eV and probably a fair bit less (there is doubt on the matter).

The protons and the neutrons in atomic nuclei weigh about two thousand times as much as the electrons—a billion electron volts, or 1GeV, where the G is for *giga*. But that's the mass of a proton standing still. Accelerate it to near the speed of light and it gets heavier. Things get more massive as they approach the speed of light; as a result, accelerating them further takes ever more energy and provides ever less by way of added speed, which is why nothing can ever be accelerated beyond the speed of light. The particle accelerator at Fermilab in Illinois, the most powerful in the world, accelerates protons to within about 100 meters a second of the speed of light, and in so doing multiplies their mass a thousandfold, from 1GeV to 1TeV. That is why the machine is called the Tevatron.

For earthbound particle physics, a trillion electron volts is currently the point where the buck (or, more accurately, the gigabuck) stops. The 10TeV protons that will be produced in Europe's Large Hadron Collider are still five years and about $3 billion away. For physicists studying cosmic rays, though, 10TeV is commonplace. Cosmic rays are particles that can contain thousands and even millions of times as much energy as one of the Tevatron's massively pumped-up protons. They are evidence of natural accelerators beyond the earth that are of either prodigious size or prodigious power. Around the world, there are various arrays of detectors that pick up the showers of energy these particles give off as they pass through the earth's atmosphere.

But even cosmic rays cannot be arbitrarily powerful; theory predicts that at more than a few million TeV, the number of cosmic rays should quickly drop to zero. The problem is that the cosmic rays do not seem to have heard the news. The number of hundred-million-TeV cosmic rays seen by cosmic-ray telescopes is very small—but it is not zero. Some of the traces seen may even reach a billion TeV—a zetta-electronvolt. And there are hints that some of the zettavolt particles may be neutrinos.

The punch that these zettavolt particles pack is extraordinary. Each of them carries an amount of energy similar to that of a cinder block dropped on your foot, or Pete Sampras's first serve. When the particles release that energy by interacting with other matter, the right instruments can detect the radiation given off from a distance of a quarter of a million miles—that is to say, the distance from the earth to the moon.

When a cosmic ray traveling through space within a micron per millennium of the speed of light hits the moon, it explodes into a vast shower of secondary particles. This shower will start off moving almost as fast as the original particle, and will thus be well over the speed of light in the rock through which it is traveling. When charged particles travel faster than the local speed of light, they give off a shock wave of radiation.

Normally this Cerenkov radiation—named after Pavel Alekseyevich Cerenkov, who discovered it in the 1930s—will not be detectable from the earth. Cosmic rays made of protons or atomic nuclei will be turned into showers of secondary particles as soon as they hit the surface on their way into the moon, and the broadening beam of radiation they give off will thus be pointed down into the rock. But neutrinos are different. Theory says that ultra-high-energy neutrinos are much more likely to interact with everyday atoms than their standoffish low-energy siblings—they can't pass through whole planets without noticing, as solar neutrinos do. But they can still penetrate a few kilometers of rock before giving up their energy. This means they can produce showers of secondary particles within the moon rather than just at its surface. If a neutrino comes in at a shallow enough angle, the particle shower it produces—and the Cerenkov radiation that comes with it—may head up out of the moon and into space. And sometimes such a shower will point at Goldstone.

3. Meters

Officially the 70-meter dish above the pedestal lab is called DSS14; informally it's the Mars dish, built in the mid-1960s to pick up transmissions from the first NASA spacecraft to visit Mars. Around nine o'clock on Saturday evening, when it has just finished a shift tracking NASA's fourteenth Mars mission in almost forty years, the dish is put into its stowed position, pointing straight up at the zenith, and Chuck Naudet and I climb up it. Naudet started his career working on particle accelerators, and if the Superconducting Super Collider had not been canceled he would probably now be doing experiments in vast tunnels under Texas. But it was in fact canceled, and so he ended up at JPL, working on interferometers—systems that combine the light waves or radio waves from a number of separate telescopes or dishes. Interferometry at Goldstone meant giving up tunnels for the delights of climbing dishes.

The first part of the ascent—outside the drum-shaped base of the pedestal—is on an open staircase. A few flights up, though, the drum starts to taper—this is what makes the pedestal lab's curved walls slope inward—and the ascent gets a little hairier as we start to climb ladders and strange, twisted companionways, their rungs skewed because their tops and bottoms will move relative to one another when the dish turns. It's all a bit Escher, and a bit vertiginous. Just to make it more fun, a bird-scarer right next to one of the ladders intermittently makes an extremely loud noise, which is exactly the sound that a Foley artist would select to tell you that a thousand-ton metal dish is suddenly and catastrophically beginning to collapse. The crows that roost in the framework of struts under the dish—the intended audience for these startling sound effects—ignore them completely. Unlike us, the birds are either very phlegmatic or completely deaf.

About 35 meters up, we reach a gallery tucked into the inverted canopy of the dish itself and pass through a hatch into a four-story cone within the dish, the place where the signals from space are harvested. The cone is a cramped jungle gym of grill floors stuffed with electronic equipment: it's like an upended submarine, or perhaps a space station. Four flights up, Naudet unscrews a small radio emitter from one of the equipment racks, hands it to me, and heads off up a last ladder and through a hatch in the ceiling. I pass the transmitter up to him and follow, gingerly, onto a tiny balcony near the tip of the cone. From the balcony, the bright white dish is all our world; its rim is our horizon, just 35 meters away. Above us, held in place by the dish's three great arms, is a metal mirror that bounces the radio waves gathered by the dish into the receivers in the cone beneath us.

With a little handheld antenna, Naudet starts to play a radio signal onto that metal mirror—a test signal to make sure our receivers and amplifiers are working properly. I go back down the ladder to phone the pedestal lab and see if they're picking it up, but they are distracted by some other set of worries. So we wait, Naudet up above on the tiny balcony, I down in the narrow guts of the cone, surrounded by an eerie mechanical chorus of rhythmic whirs and whistles. It is a very strange sound track for a very strange place.

Naudet has to go through this test almost every time the team uses the dish. Ideally the little antenna and its radio unit would be hardwired in position, so the test could be run just by flicking a switch in the comfort of the pedestal. But the Deep Space Network people don't like having anything hardwired into their system that could possibly produce noise. There's always a chance that it will be left on by accident and disrupt a command being sent to a distant spacecraft, or garble a vital piece of information coming back. There's also a risk to the hardware; when the big dish is used to shout at a far-off spacecraft, or to illuminate a passing asteroid for radar studies, it puts out a ferocious amount of power. The message sent to *Pioneer 10* from the dish on Friday, a message that had to be picked up far beyond the orbit of Pluto, had half a megawatt of power behind it. Naudet has seen receivers in the cone reduced to melted slag because they were left plugged in at the wrong time.

So it's understandable that the little antenna has to be taken out and aimed by hand every time it's needed. But it's also an irritation, one of the many rigmaroles that Naudet says make GLUE the hardest experiment he has ever worked on. Tying the moon to the antenna involves a ceaseless untangling of knotted cables, actual and metaphorical. GLUE is forced into small and inconvenient slots both in time and, as Naudet and I are currently experiencing, in space.

Eventually the people down below us in the pedestal pay attention, pick up our signal, and tell us they're satisfied. Putting the phone back on its cradle, I'm a little baffled by a powerful magnetic catch attached to the mouthpiece. Naudet points out, as he tosses a few minor impedimenta into a doorless closet, that as soon as the dish starts moving, the cone does, too, and everything not stuck down or bolted in place will fall or slide or roll onto the wall that contains that closet—the wall that, when the dish gets down to the horizon, becomes a floor.

4. LIGHT YEARS

When we're back down on terra firma, Naudet heads over to the control room to start the process of actually moving the dish. I stay outside in the cold desert night, looking to the east and waiting for the moon to rise. Looking to the east, though, means looking past the vast and well-lit bulk of the dish, and thus not seeing the stars. So I turn around and look to the west. As my eyes grow accustomed to the dark, the sky becomes crowded with stars, the Milky Way a trail of diamond dust, the familiar constellations bizarrely bright in front of it. The cold makes the sight feel all the clearer.

Everything that I can see is within our galaxy, tens of thousands of light years away at most. The light from the brightest star, Sirius, has been traveling only a few hundred million seconds—it's not even as old as I am. The next night, Peter Gorham points out the great spiral nebula in Andromeda, our galaxy's nearest neighbor and pretty much the farthest object you can see with the naked eye. But even that is only two million light years away.

Two million light years is nothing compared with the depths the zettavolt neutrinos might come from, or compared with the distances radio astronomers treat as routine. But, gazing up into the desert sky, I can't feel that there is any way that actually seeing farther could feel like seeing farther. It already feels like looking out forever.

When I turn back to the east, the moon is already up, fat and yellow on the horizon, its shadowed dark side like a hood above its face. And as silently as the moon has risen, the great dish has begun to turn. That something so large should move at all is a wonder; that it moves so smoothly and swiftly and silently is a shock. Within minutes, it has settled its aim: but not on the moon. Instead, it is looking at a spot of sky in the constellation of Virgo that lacks any visible distinguishing mark.

There, too faint a source of visible light for the eye to see, is a quasar called 3C273, a vast black hole spewing out radio waves like a beacon. 3C273 is a thousand times as far off as Andromeda, two billion light years away. It is as bright as a hundred normal galaxies; a jet of hot gas longer than our galaxy is wide belches out to one side of it. Extraordinarily distant, unthinkably powerful. But to the GLUE team, 3C273 is basically a scaled-up version of the handheld antenna Chuck used in the cone. It's just another part of their routine calibrations, something with which they can check out their instruments before they go after the really weird stuff.

5. KILOMETERS

At the same time as the great seventy-meter dish turns to quasar 3C273, so does a smaller dish at the other end of Goldstone, fourteen miles up the road. DSS13, a 34-meter antenna used exclusively for research, is the other part of GLUE. At the speed of light, the two dishes are about 70 microseconds apart. That means that signals from the moon—or almost anywhere else—will arrive at the two dishes at different times. If the data from DSS14 and DSS13 show paired events offset in time by just the amount that would be expected if the signals had come from the moon—an offset that constantly changes as the moon moves across the sky—then that would be pretty good evidence that the moon was really the source.

Most radio telescope sites don't have dishes a long way apart connected by high-bandwidth optical fiber. But at Goldstone, the dishes are at a number of different sites, for fear of interference. And so while Naudet and I were up in the cone, David Saltzberg was off at dish 13, checking its systems in a similar way (though from the comfort of a nice warm and immobile lab). Now the two dishes are both attending to the high-frequency variations in 3C273's radio output so that the time delay in the cables connecting them can be calibrated. It should be the same as it always is—but it's another thing that has to be checked again every time. "Anything we don't check, turns round and bites us," Naudet explained to me in the cone.

Once satisfied with dish 13, Saltzberg drives back through the empty desert to join us at the pedestal. It takes him rather longer than 70 microseconds. But it also gives him the opportunity to watch a coyote carrying off a rabbit, and to wish on a shooting star.

6. SECONDS

A bit after ten, we start taking data. Saltzberg has plugged a timer with various LED counters on it into one of the racks of amplifiers and computers in the pedestal lab. When the analysis system gets turned on, the numbers on its top readout shoot up, climbing into the thousands in just a few seconds.

The readout is counting the number of times the new veto system gets set off by local radio interference. By stopping and starting it again and again, Saltzberg eventually convinces himself that the local receiver is interrupting the flow of data with 300 vetoes a second; if the counter gave off sound instead of counting in light, we'd be hearing something like the D above middle C. This sounds like bad news to me; if the experiment is switching itself off 300 times a second, how can we be expecting any data? Then I do the math. Three hundred vetoes, each 500 nanoseconds long, means 150,000 nanoseconds of veto every second. That's 150 microseconds, or just over a tenth of a millisecond. For the other 99.9 percent of that second, the experiment is working just fine.

When people were explaining the vetoes to me with diagrams on the lab's whiteboard, when we were hunting down spare nanoseconds by the meter, 500 nanoseconds came to feel like something tangible, something everyday and commonsensical. But if you're not living at the speed of light—if you're living in a world where a second is just the tick of a clock, rather than time enough to get most of the way to that big fat yellow moon—500 nanoseconds is as close to nothing as makes no matter.

Climbing steel ladders high above the desert isn't the only way to get vertigo out here. The numbers will do it to you all on their own.

7. Hours

With the veto system working, the team settles in for the run. Dawn Williams, the graduate student, is in charge of actually taking the data. Events the system thinks worth recording turn up once every minute or two, and Dawn downloads recordings of these events to disk every time there are twenty-five of them. Everyone else just sits around. There's nowhere to go: the main base at Fort Irwin is almost twenty miles away and offers civilians only a Burger King and a bowling alley, both closed by this time of night; Barstow, the nearest town, is a good hour's drive through the desert. Anyway, they all feel that if they went away something would go wrong. So we sit, and occasionally make a sandwich from the weekend's worth of cold cuts in the fridge, which is all we have to eat, and talk. We talk about physics.

It's a bit like a very long episode of *Seinfeld,* except with everything replacing nothing as the subject matter, and rather less likely to make you laugh out loud. The talk just rolls on and on across the universe. Naudet and Liewer spend a while discussing whether a new sort of interferometer for taking pictures of planets outside the solar system will work out as well as some people seem to be saying, and decide that it probably won't. "They're still at the pre-subtlety stage," Kurt says with a grin.

He wanders off as Naudet and I discuss theories about conditions for life on those as-yet-to-be-seen planets. Then Saltzberg manages to ensnare us all in a conversation about how best to prove to undergraduate students that light is made up of electromagnetic fields. This one drags on for an hour, with Peter offering effects that might serve and David arguing that they could be explained by other means. In almost every discussion, Gorham and Saltzberg will take different sides; there's something a little competitive about it.

Then Naudet, following up on something that Saltzberg mentioned in an earlier discussion about terrorism, finds an article on the Web about a Boy Scout who built a primitive breeder reactor in his mother's garden shed, irradiating thorium from gas mantles with a neutron gun made from the traces of radioactive americium found in smoke detectors. Saltzberg and Naudet agree that if they had known making uranium-233 this way was possible when they were kids, they probably would have tried it themselves instead of just making chemical explosives, as they did. The events tick away on Dawn Williams's screen. Every so often, there's a flurry of activity as one set of readings ends and the next is begun. Then, at 3:00 A.M., our session is over, and it's time to drive back to the dormitory and collapse.

8. MEGAPARSECS

The search for ultra-high-energy neutrinos that provides the occasion for these late-night bull sessions is a by-product of the discovery in the 1980s of cosmic rays with more energy than was previously believed possible. The reason they were supposed to be impossible stemmed from another of the strange effects of traveling at extraordinary speed. When two objects are moving with respect to each other, the radiation traveling between them reflects the fact. If they are moving toward each other, the wavelengths shorten—a blue shift. If they are moving apart, the wavelengths lengthen—a red shift. The red shift in the light from quasar 3C273 reveals it to be running away from us at about 16 percent of the speed of light—48,000 kilometers a second—because of the expansion of the universe.

The expansion of the universe is one of the crucial pieces of evidence for the big bang. Another is the cosmic microwave background, a faint glow that suffuses all of space and provides about 10 percent of the static in television broadcasts. This background buzz provides scientists with a way of examining what conditions were like in the early universe—a spacecraft devoted to this study is one of the missions that the big dish is keeping in touch with this weekend when it is not looking for neutrinos. And the cosmic microwaves should also keep the universe free of the highest-energy cosmic rays.

Imagine the universe as seen by such a cosmic ray—by a 50-million-TeV proton traveling within a whisker of the speed of light, say. Its speed blueshifts the gentle low-energy-microwave background into an oncoming blizzard of high-energy gamma rays so powerful that the proton will be knocked to pieces if it hits one of them head on—as eventually it must. On average, a 50-million-TeV proton should be able to make it through the blue-shifted onslaught of gamma rays for only about twenty million light years before decaying.

Twenty million light years—or six megaparsecs in the units that astronomers prefer—is a long way by the standards of the stars visible in the night sky: ten times the distance to the Andromeda galaxy. But by the standards of the cosmos as a whole, it's tiny. It's only a hundredth of the distance to 3C273—which is one of the nearest of the quasars. And this is why the detection of particles well above the 50 million TeV cutoff by cosmic-ray telescopes is so fascinating.

Astrophysicists believe that cosmic rays are particles accelerated by magnetic fields associated with stars and galaxies; the degree of acceleration depends on the strength of the field and the size of the source. Jets from quasars might be able to produce 100 million TeV particles; so might the fierce magnetic fields around pulsars—the collapsed remnants of supernovas. But the destructive powers of the blue-shifted microwave background rule out quasars as a source for the most energetic cosmic rays—they're too far away for the particles to get from there to here intact. And if the sources were pulsars, then the cosmic rays would come from parts of the sky where there are pulsars. But they don't. With only a handful of really high-energy cosmic rays ever seen, it's hard to say whether they come from all over the sky or from a few specific sources. There are people willing to argue it either way. But none of the people who trace the rays back to specific points in the sky have found those points to be close to anything that looks like a cosmic-ray generator.

At this point, where astrophysicists find themselves at a loss, other sorts of physicists start to get interested. Maybe these particles aren't low-energy things that have been gradually accelerated. Maybe they start off with extraordinarily high energies, created in all their glory by some weird, wonderful, and as yet undiscovered precursor. If so, ultra-high-energy particles are the keys to a new world of physics—a world that particle physicists couldn't reach in their laboratories even if their accelerators took over the solar system. This is the domain of the wimpzillas—a generic name for astonishingly massive, almost stable particles predicted by all sorts of theories; and of the cryptons, a particular type of decaying wimpzilla predicted by string theory; and of other fevered theorists' fancies. This is the shadow realm of the Z burst, in which inordinately heavy neutrinos from the dawn of time interact with rafts of commonplace neutrinos around nearby galaxies to produce sudden explosions of new particles, including ultra-high-energy cosmic rays. This is a world where twists in the fabric of space and time are imagined unraveling with energies that, for a moment, rival the big bang itself.

One of the things these groovy "top-down" explanations for the highest-energy cosmic rays have in common is that they all produce ultra-high-energy neutrinos. "Bottom-up" accelerator-based explanations don't. Accelerators can work only on charged particles, such as protons or atomic nuclei. And while the interaction with the microwave background that must slow such particles down will produce neutrinos, those neutrinos will always have less energy than their progenitors. If neutrinos found in the zettavolt range were to be produced in this way, their cosmic-ray progenitors would have to be in the 10ZeV range, which would be unbelievably high for any process depending on a natural particle accelerator such as a pulsar.

So if GLUE finds neutrinos in the zettavolt range, it's pretty much a sure thing that they will have come from something new, weird, and fascinating. There'll be a lot of uncharted physics out there to explore, perhaps just a few megaparsecs away.

9. YEARS

While neutrinos don't interact with ordinary matter much, they can leave quite a mark on an impressionable imagination. They strike at random in physics courses the world over; something about how hard they are to capture, their tiny masses, their strangely oscillating identities, and their promises of astrophysical delight will seize a student's fancy and not let go. "Some people get bit by them," Gorham says late on Sunday night.

The neutrinos got their tiny teeth into Gorham when he was at the University of California, Irvine, in the late 1970s. He had gone to college to study literature, but once there he found he wanted something that offered a little more certainty than literary criticism, and migrated to astronomy and then to physics. In the physics department, he met Fred Reines, who in the 1950s had built the first experiment ever to detect neutrinos. Given the fugacity of his quarry, Reines originally expected to have to set off an atom bomb to make enough of them for his detector to get a signal, but in the end he found that he could make do with a nuclear reactor. Reines's interest in detecting neutrinos—in particular neutrinos from natural sources like suns and quasars—was shared by his former student John Learned, also at Irvine. Learned went to Hawaii in 1981, and Gorham followed, doing his doctorate at the University of Hawaii.

Gorham returned to the mainland to do non-neutrino astrophysics at Caltech as a postgrad, but came to find it somewhat unsatisfying. The observations were challenging to make and interesting to think about, but they didn't really tell anyone anything new about the universe; it was "butterfly collecting with galaxies," he says. So he went back to Hawaii to play a part in the DUMAND experiment that Learned was leading. DUMAND—Deep Underwater Muon And Neutrino Detector—was an attempt to pick up relatively low-energy neutrinos passing through seawater, using deep-water cables garlanded with light detectors to see flickers of Cerenkov light in the otherwise dark abyss. The same technique is now being used with detectors embedded in the ice at the South Pole, and there are underwater detectors like DUMAND being developed elsewhere. DUMAND itself, though, never got finished. Amid technical difficulties, problems with noise—the abyss is not as dark as one might wish—and a falling out with the project's paymasters at the Department of Energy, DUMAND was canceled in the mid-1990s. Gorham left for JPL, which had been thinking about getting into the neutrino-detection business; but by the time he got there, that project, too, had foundered. He found himself back in regular astronomy, working on space-based interferometers.

One day in 1997, Gorham came across a paper by Ron Ekers, of the Parkes radio telescope in Australia, and Tim Hankins, of the Very Large Array, a radio-telescope interferometer in New Mexico. They had used the Parkes dish—a telescope that supplemented the Deep Space Network during the *Apollo* missions, a role dramatized in the exquisite Australian film *The Dish*—to try to measure the radio Cerenkov from neutrinos hitting the moon, an idea first suggested by a Russian theorist, Igor Zheleznykh, in 1988. They hadn't looked for long, they had used a method that probably wouldn't have worked, and they hadn't found anything anyway. But they had published, and for that Gorham professes himself eternally grateful. "People don't like to publish zeroes," he says, but they really have to—otherwise what might be promising steps toward a new technique get taken in isolation and never put together. Gorham had heard about Zheleznykh's idea back in 1988, but hadn't seen how to build an experiment that would capture the effect. Normal approaches to radio astronomy just don't lend themselves to the capture of discrete events. Now Ekers and Hankins had shown him how. He went to his officemate, who had a radio-interferometry experiment running at Goldstone, and said, "We should try this." Gorham now recalls that "within a microsecond," Chuck Naudet, the one-time particle physicist, took in the possibilities and said yes. And so GLUE was born, borrowing observing time and equipment from Naudet's work on a project to link earthly dishes to a Japanese space-based radio-telescope—the same project from which the vital 500 nanoseconds of cable were filched this Saturday evening.

Shortly after GLUE got started, Gorham gave a talk at UCLA. David Saltzberg found it fascinating. Unlike the JPLers, Saltzberg has always been pretty much a straight-down-the-line particle physicist. But then GLUE is in many ways more like particle physics than like traditional astronomy. It looks for events, not things; it filters its signals through a series of real-time electronic triggers that separate the wheat from the chaff rather than analyzing the data later. The problems with the veto system that cropped up on Saturday afternoon are exactly the sorts of problems particle physicists are used to. Indeed, Saltzberg faced an almost identical interference problem—involving exactly the same piece of equipment, the workhorse 222, and its inability to launch a veto within a veto—when he first started working in the tunnels of the Tevatron as a postgrad. (The fact that the solution he came up with then couldn't be applied this time irked him a bit.) So GLUE sits quite happily with his more mainstream work on a large experiment at Fermilab. It offers the pleasures of a strange topic and a small team, and the possibility of a big slice of something exciting. "It's the high-risk, high-gain part of my portfolio," he explains.

Interest—and some money—from UCLA made JPL take GLUE more seriously. In the early days, Gorham, Naudet, and Kurt Liewer had been setting up all their equipment from scratch every time they came out into the desert to collect data. Once Saltzberg was on board, they got some dedicated racks for their very own 222s and such—racks they could leave wired up from visit to visit. Time was found to do some experiments at the Stanford Linear Accelerator, or SLAC, to show that neutrinos really could produce radio waves in the way that theory—theory developed by another Moscow theorist, Gurgen Askaryan—suggested. The most powerful and precise electron beam in the world, capable of focusing its energies to within a micron of the required aim point, was used to shine 3GeV gamma rays into a four-ton sandpit built specially for the occasion. A pulse of ten billion 3GeV gamma rays was deemed a pretty good stand-in for a single ultra-high-energy neutrino, and when hit by such pulses the sand gave out exactly the squeals required. Dawn Williams, new on the team at the time, remembers getting almost all the results they needed in the first morning they took data. The team's senior members spent the rest of their days at SLAC trying to impress on her that most experiments were nothing like that clear-cut.

More than twenty years after getting bitten, Gorham is still convinced that neutrinos could be the wave of the future in astrophysics. Ultra-high-energy neutrinos, he points out, are the only high-energy particles to which the universe is transparent—there's tenuous stuff of various sorts between the stars, be it gas or gamma rays or infrared light, that will stop everything else, from protons to photons, over a long enough distance. Neutrino telescopes will shed new light (or, rather, not-light) on things astrophysicists have already observed by other means; they will also see things no other instruments can detect. Unfortunately, to date, telescopes devoted to neutrinos have seen only the sun and, on one occasion, a supernova. Most of their work has consisted in setting limits on their own sensitivity—of publishing zeroes and trying to say what those zeroes mean. As Gorham pointed out when recalling the paper by Ekers that got GLUE started, publishing these zeroes is vital. But it's a little depressing when it starts to take up a significant part of your career. For Gorham, a devotion to the promise of neutrino astrophysics has meant publishing a lot of zeroes of his own.

10. One Particular Microsecond

So far, in terms of its published results, GLUE is another zero. The team has not seen a single event that meets the criteria Gorham originally set down for a cast-iron, sure-thing, neutrino-hitting-the-moon signal. But it has seen something that's, well, odd.

All radio receivers—even those thousands of miles from war games—are susceptible to spurious signals in their output produced by random noise. To sort interesting bursts of radio waves from these spurious signals, GLUE takes signals seriously only when the second receiver, DSS13, also sees a signal within 70 microseconds of a signal at the big dish; signals any further apart than this cannot be related, because at the speed of light the dishes are only 70 microseconds apart.

Once the experiment has picked up a pair of signals close enough together that they might come from the same source, the next step is to find out whether or not that source is the moon. The difference in the lengths of the two long sides of the triangle formed by the two dishes and the moon defines exactly what the delay on a signal from the moon should be, and this delay changes minute by minute as the moon moves across the sky. So to see if a pair of signals could have come from the moon, the GLUE team takes the difference in the signals' time of arrival at the two receivers and subtracts the delay expected for a signal from the moon. If taking the observed delay from the predicted delay leaves them with zero, it looks as if GLUE has seen a signal from the moon.

If the signals are noise—and random bursts of noise at the two antennas can be expected to coincide every five minutes or so—then subtracting the observed delay from the predicted delay will produce zeroes no more or less often, in the long run, than it will produce any other number between –70 and +70. If the signals really are coming from the moon, there will be a peak in the number of signals right on the zero. However, when Chuck Naudet analyzed the early GLUE data this way in 2000, the graph he plotted showed neither of these things. In addition to a steady background of events everywhere between –70 and +70, he got a sharp spike in the number of signals at one specific delay. But this peak was not on the zero—it was just off to one side. It was more or less exactly one microsecond off.

Faced with this anomaly, the GLUE team went through all the links in its experiment again with obsessive care. Naudet checked all his calculations forward and backward. Kurt Liewer reexamined the technique he was using to calculate the expected delays from the position of the moon. The exact delay that resulted from the cabling between the dishes was measured again and again. The pre-observation calibrations were broadened to include quasars all over the sky. And everything checked out fine. There was no way they could find a spare microsecond in the system. But there was also no obvious way to explain a spare microsecond in the universe, either. Taken at face value, the data say that there are mysterious signals coming from a point about one lunar diameter away from the moon. There are various ways zettavolt neutrinos might be produced from seemingly empty space; but how could the empty space producing them move across the sky in lock-step with the moon? During its long nights in the pedestal lab, the GLUE team has tried to dream up ways that sprays of particles might emit radio waves only well after they have left the moon; but their suggestions are barely even ready for bull sessions in the small hours, and certainly not ready for prime time.

For a while, the best way of explaining this one-microsecond-off peak—the Naudet peak, as Saltzberg calls it in order to tease Naudet—was to say that it was a fluke, and that over time the noise level at all the other delays would build up so that it no longer looked significant. But this has not turned out to be the case. The peak is still there, and growing. On Sunday afternoon, while sorting through the data gathered the night before, Dawn Williams comes across yet another one: event twelve of the fifth series, gathered at 01:15:04 PST on Sunday morning. The peaks from the two receivers are strong and look very similar; the delay between dish 13 and dish 14 is just about a microsecond away from the delay expected for a signal from the moon. It is, Gorham says, the best potential signal they have ever seen. During the afternoon, he and Saltzberg cover up yet more of the lab's thickly scrawled-on whiteboard calculating the odds against a match this good being due to chance. They come up with some big numbers. Once they have the numbers, they get into a disagreement about the niceties of their statistical interpretation, a disagreement that gets increasingly snippy. By this point, we have all been in the windowless lab, the empty desert, or the spartan dorm for a long time, and it's beginning to show.

When Gorham draws me a diagram to explain the problem, I can see at least three earlier versions of the same sketch—a slightly squiggly horizontal line with a big peak right next to a dashed vertical line—in various different colors and degrees of erasure and overwriting elsewhere on the lab's whiteboard. The peak has become part of the furniture. It's almost as if it's another member of the team, sitting quietly in the background, always available to spark another late-night discussion. Saltzberg is fond of it. He thinks it keeps things interesting; without it, GLUE would just be setting limits above which nothing seems to be happening. Gorham, I think, is more irritated by it. After all, if it was one microsecond to the right, his experiment would have made a real and important discovery. A sizable surplus of events coming directly from the moon would definitely be taken as evidence of something new and real even if none of the signals was quite the cut-and-dried neutrino event the team really wants. But it's not exactly right, and it's not going away, and it still raises the possibility that the team has made some sort of systematic error. Peter Gorham gave up literature for astronomy out of a desire for right and wrong answers. Now he's stuck with an extraordinary *maybe.*

11. MINUTES

Just before five o'clock on Monday morning, Williams and Saltzberg—who have been in the pedestal lab pretty much nonstop for about seventeen hours—and I go outside for a few minutes to catch a celestial coincidence. Much taken by the clarity of the sky, and with a lot of time on my hands, I have been looking at astronomy Web sites. One of them tells me that the space shuttle *Columbia,* which is servicing the Hubble space telescope, is about to pass overhead a bit to the south of us—and at the same time, but in a very different orbit, so is the International Space Station. Once we walk past the floodlights of the 70-meter dish's compound, our eyes quickly grow accustomed to the dark. The spacecraft are fairly easy to pick out. The shuttle and the Hubble appear first, fused by distance into a single star, and pass quite close to the moon, which by this stage in the night is a clean bright silver. The space station comes out of the earth's shadow a little later and a little lower in the sky, climbing steadily until it crosses the descending path that the other spacecraft has traced; at one point, they look only about 10 degrees apart. There are ten human beings not on the earth tonight, and we can see the vehicles carrying them all. They are about as far away from us as Salt Lake City, or maybe Denver, their two little stars crossing the sky as smoothly as the great dish behind us turns on its bearings. Orbiting at almost 8 kilometers a second, within a few minutes of appearing they have fallen into the dawn that we won't see for an hour.

It's a sight worth getting cold again to see.

12. CUBIC KILOMETERS

In about five years, another shuttle mission may lift a very different sort of telescope to the space station—one for looking down on the tracks of ultra-high-energy cosmic rays. From the space station or a satellite, you can see a lot more of the atmosphere beneath you than an array of telescopes looking up from below can, which is why the cosmic-ray-physics community is interested in putting detectors on the space station—a proposal called the Extreme Universe Space Observatory (EUSO)—or on independent satellites, a proposal called the Orbiting Wide-angle Light collector (OWL, not to be confused with the identically acronymed European proposal for an OverWhelmingly Large telescope, an optical system that would boast a glass mirror larger than Goldstone's 70-meter dish). The area of the earth's atmosphere that could be inspected by the OWL system would be similar to the area of the moon that GLUE watches today, and OWL would be a lot more sensitive.

Gorham, though, has his eyes on different targets. One is Antarctica. There is already a small neutrino telescope similar in concept to DUMAND embedded in the ice at the South Pole, and there are plans to expand it to a cubic kilometer. That array—known as Ice Cube—should be big enough to see the tracks of neutrinos from some astrophysical objects, but it will not be big enough to see the much rarer ultra-high-energy neutrinos. To do that, Gorham intends to use the whole of the Antarctic ice cap. He and the GLUE team, along with colleagues from a range of other institutions, are proposing an experiment called ANITA (the Antarctic Impulsive Transient Antenna) that will be lifted high above the ice on a balloon and look down for Cerenkov radio waves. Because ice is very transparent to radio waves—radars can see all the way through the ice cap to the hidden rock below—

ANITA should be able to pick up neutrino Cerenkov bursts from tens of thousands of cubic kilometers of ice at a time as it drifts in a month-long circle around the pole.

The particular charm of ANITA is that it is almost guaranteed to find something. Whether or not there are cryptons and wimpzillas and cosmic strings churning out neutrinos with ludicrously high energies, there are certainly some very-high-energy cosmic rays. Even if these are not neutrinos, the fact that some are getting through means that others are being stopped by the vicious gamma-ray beating administered by the cosmic microwave background. That beating produces short-lived particles that, when they decay, yield neutrinos with maybe a tenth of the energy of the original particles. So the slowing of cosmic rays like those already seen must give off neutrinos with energies around a million TeV. GLUE is not sensitive enough to pick up neutrinos in this (comparatively) low energy range—but ANITA would be.

In the spring of 2002, ANITA was seeking funding from various parts of NASA. It has since received it, and should fly in 2006. At the same time, the GLUE team was looking at another type of detector—a salt dome. Large deposits of pure salt are potentially great ultra-high-energy-neutrino detectors because they are almost perfectly transparent to radio. With volumes of 50 to 100 cubic kilometers, salt domes are much smaller than the Antarctic ice cap. But ANITA would detect only radio waves that came out of the Antarctic ice at certain oblique angles. A ring of small cheap antennae surrounding a salt dome could catch all the radio emissions coming out of it, and thus use its cubic kilometers far more efficiently than GLUE uses the moon or ANITA would use Antarctica. And the salt-dome site would be able to take data all the time, rather than just using scraps of time at Goldstone left over from the Deep Space Network schedule, or the span of a relatively short balloon trip. It might get a hundred events a year, every year.

Fiddling with the details of GLUE for yet another shift makes these prospects for the future look enticing. But projects in Liewer's "pre-subtlety phase" always look good. When Naudet says one night that it will be ANITA that "gets it done"—that finally opens up the world of ultra-high-energy neutrinos to inspection—Saltzberg reminds him that that project will have "all the problems of this one, but at 130,000 feet." Gorham is enthusiastic about the salt dome—a hundred events a year is "fat city in neutrino astronomy." But the others on the team remember the trip they made to the Hockley salt mine in Texas to check out the radio transparency of the salt; while the results were good, the experience of working in a salt mine, they all agree, was completely horrible.

In the meantime, the Goldstone work continues. And there's the possibility of starting to work in Australia, too. Ron Ekers, director of Australia's radio-telescope observatory, has watched with interest as Gorham has improved on the techniques Ekers first used to try to detect neutrinos hitting the moon. In Australia, they could make use of two dishes linked by fiber, just as they have at Goldstone, and get a lot more observing time with no war games next door. There will still be the problems inherent in an experiment one end of which is totally inaccessible. But seeing 100,000 cubic kilometers of moon rock all at once still makes facing them worthwhile for the time being.

13. DAYS

Eventually we emerge from the pedestal into the early March sunshine. The dish above us has been stowed, pointing straight up at the blue sky, and it will stay that way for a few hours of maintenance. By this afternoon, it will be back at work bringing home data from NASA's far-flung envoys to the solar system.

The sun is already powerful enough to prickle the skin; the moon is beginning to drop toward the bare mountains of the west. Its hard nighttime silver is softened in the blue of the day. We drive back toward the dorm nursing the body-clock weirdness of three night shifts; some will rest up a few hours, some will make their way back across the desert toward Los Angeles more or less directly. In three days, GLUE has taken about ten more hours of data, increasing its cumulative observing time by about 10 percent. This is now the pattern for GLUE. Each time the team gets a few days for observations, there will be new problems to sort out—one of the receivers started misbehaving in the last hour of this latest observing run, and is now at the top of the "to fix" list—but though the problems will change, the rhythm of the days probably won't. Once, every observing run meant a lot. Now each day adds to the whole only incrementally. The excitement that came from the very idea of searching for these wild particles has worn off, at least to some extent. So has the buzz of improving the system every time it is used. The anomaly of the one-microsecond-off peak rankles as much as it excites; the team has to assume that it's just a statistical fluke, but it will be years before there's enough data to show that for sure. So it won't go away, and it won't come into focus.

But despite the fatigue and the frustrations and the lure of future projects, in three or four months the team members will be back for a few more days. And the fact that those few days will be in some way routine should not diminish their wonder. For a few days, the great dish behind us, the smaller dish over the hills, and the fading world in the western sky will again be tied into a nanosecond net for catching passing zettavolts. For a few days, five people in a windowless room will look for something utterly extraordinary. For a few days, the earth will open a strange new eye to things no one has yet seen.

If there's a beauty in trying to understand the cosmos, it's in days like these.