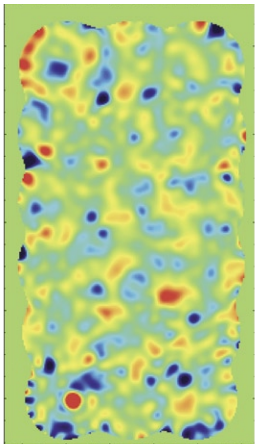
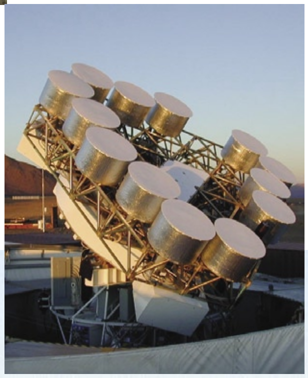
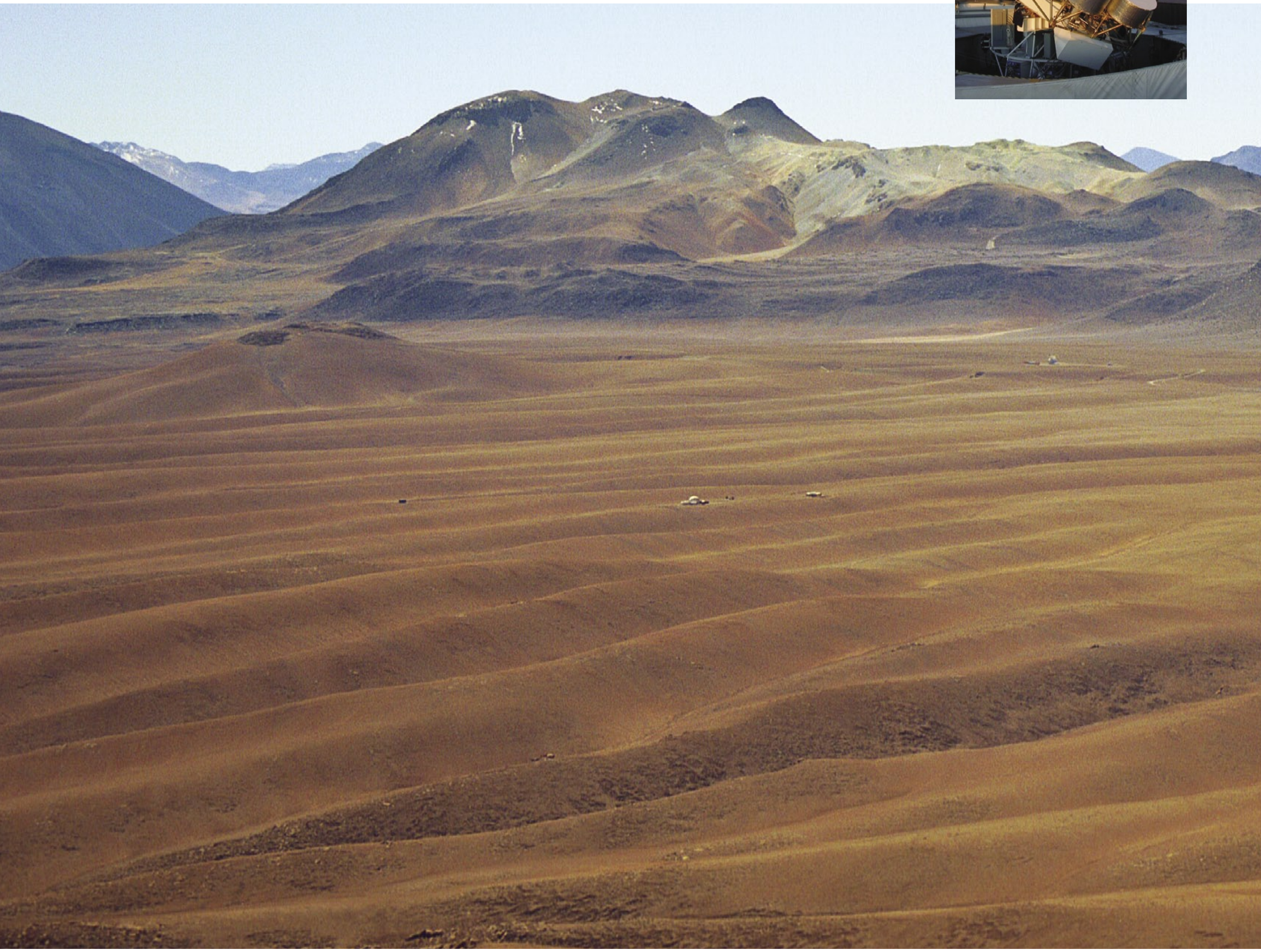


Below: For more than five years the Cosmic Background Imager has had the vast, high Chajnantor plateau virtually all to itself. Its dome can be made out in the center of the picture below, with its generator about an inch to the right. The clamshell dome (right) is made of sailcloth, flexible enough to withstand 100-mph winds; when it opens, the CBI can train its 13 antennas (far right, in their original configuration) on the microwave background radiation, emitted 400,000 years after the Big Bang. Recent polarization experiments on the tiny temperature fluctuations in this radiation have revealed primordial matter bunching into the seeds of our present-day galaxies (left).





"You go up there with this instrument, and you're collecting photons that haven't interacted with anything for the last 13.8 billion years."

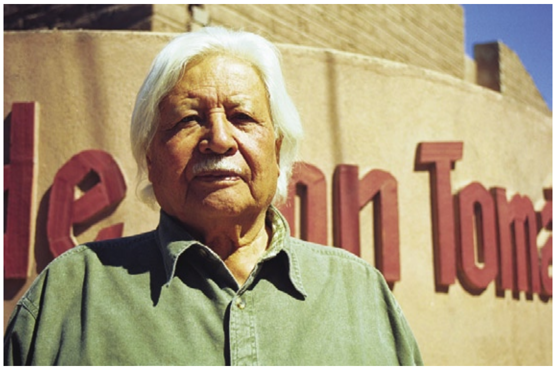
The Caltech–Chile Connection

by Jane S. Dietrich

From its high, dry site on the Llano de Chajnantor in Chile's Atacama Desert, the Cosmic Background Imager (CBI) peers back 13.8 billion years, searching for tiny fluctuations in temperature encrypted on the microwave background radiation, the fossil radiation left over from the birth of the cosmos. That radiation, the most ancient light in the universe, was emitted just 400,000 years after the Big Bang (the equivalent of about 45 minutes after conception when compared to a human life). It's the epoch when light and matter decoupled, when protons and electrons got together to form atoms, so that the electrons stopped scattering photons, freeing them to travel across time and space into the CBI's antennas. Tony Readhead finds it "miraculous." You go up there with this instrument, and you're collecting photons that haven't interacted with anything for the last 13.8 billion years."

Those collected photons gave Readhead and his colleagues the first glimpse, in January 2000, of primordial matter beginning its collapse into the clumps that would eventually evolve into clusters of galaxies. More recently, polarization observations have revealed the dynamics of that clumping—data just published last fall.

Plucking 13.8-billion-year-old photons out of the sky is not, obviously, an easy task. Llano de Chajnantor, at 5,080 meters (16,700 feet) in the driest place on Earth, looked to be an ideal place from which to attempt to see this ancient light. The area was first explored in 1994 by a combined team from the American NRAO (National Radio Astronomy Observatory) and the University of Chile Astronomy Department, prompted by earlier measurements of the atmospheric opacity obtained by a team of Japanese astronomers in the nearby highlands. In that year the NRAO put up a test site, getting "incredible" results. "It's the best easily accessible site in the world for radio astronomy," Readhead, the Rawn Professor of Astronomy and the CBI's principal investigator, claims, with at



Near the end of its journey from Pasadena, the crated telescope approaches San Pedro de Atacama.

Don Tomás Poblete (above) built a comfortable headquarters for the CBI crew at his San Pedro de Atacama hotel, La Casa de Don Tomás (top, with the Licancabur volcano in the background).

least 330 observing days annually and almost no moisture to interfere with the incoming radio waves. "Easily accessible" may be in the eye of the beholder, but Readhead and his optimistic team were the first to seize the opportunity to build an observatory there, with a little help from some new Chilean friends—not just other astronomers, but also a lawyer and a landowner.

Chile's high, dark expanses with exposure to the southern sky and unrivaled "seeing" have lured foreign astronomers for decades, and the nation has always welcomed the astronomers and tried to make it comfortable for them to come. Numerous American, European, and, lately, Japanese telescopes dot the lengthy Andean range. While most of these observatories are located within logistical reach of Santiago or at least another city, Readhead's coveted site lay in the remote northern desert near the Bolivian border, where virtually nothing grows and few human artifacts existed.

"Pioneers have all the fun," Readhead now says, somewhat wryly, remembering the myriad problems. His was a comparatively small operation—just himself and a handful of Caltech postdocs, research faculty, members of the professional staff, and grad students—without the enormous resources of the larger astronomical communities, many with government backing. This was not Big Science, by any means. Readhead had started designing the CBI in 1987, working on key aspects of the architecture with Charles Lawrence at JPL, grad student Steve Myers, and several Caltech undergraduates in the early '90s; then he, Steve Padin, member of the professional staff, and engineer Walt Schaal (BS '58) proceeded with the detailed design in 1993 (*E&S*, 1996, No. 4). It was initially funded jointly in 1995 by the National Science Foundation, a generous gift from Maxine and Ronald Linde and funds from the Provost's Office, and was built at Caltech next to the cogeneration power plant's cooling towers on Holliston Avenue.

But before tackling the logistical problems of importing a telescope to Chile and hauling it up a remote mountain, first the legal issues had to be faced. The Santiago branch of a large American law firm proved both expensive and ineffective. In June 1997, however, at the NRAO in Charlottesville, Virginia, Readhead met with Leonardo Bronfman, former chair of the University of Chile astronomy department and member of the Chajnantor exploration team, who offered the support and collaboration of his department and pointed out a unique law that enabled foreign astronomical institutions affiliated with that university to bring instruments into the country free of the 35 percent import duty and to operate without paying the 19 percent sales tax. Subsequently, Readhead was introduced to Juan Enrique Ruiz, a lawyer at the university who was experienced in helping foreigners set up complex technological enterprises in Chile. Ruiz, along with Bronfman and Jorge May, a radio astronomer at the University of Chile, smoothly guided the Caltech group over the bureaucratic hurdles and through the paperwork—"all the stuff we didn't have a clue about how to do," says Readhead. For example, they helped him obtain the official permission to install the CBI at the Chajnantor site, a science preserve then administered by the Chilean Consejo Nacional de Investigación Científica y Tecnológica, which was also very supportive. Ruiz remains a loyal friend of the project and still helps out—most recently with new generator contracts—largely out of good will rather than for a hefty fee.

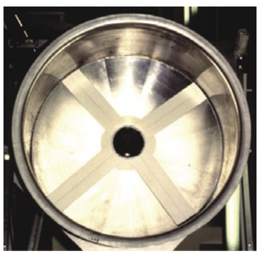
The Chajnantor site is remote, but there *is* a pleasant village 40 kilometers away and about 2,500 meters lower. An oasis frequented by pre-Columbian inhabitants, the town of San Pedro de Atacama was founded by conquistadors in the 16th century and remains popular with tourists who love the desert, particularly Europeans. It doesn't have paved roads, but it does have a couple of decent restaurants and a handful of hotels. Because the

CBI was originally planned as a two-year project, it didn't make any sense to buy or build a permanent place to stay, but the astronomers would have to sleep somewhere. While the CBI construction was finishing up in Pasadena, Readhead was scouting his Atacama site, where Angel Otarola of the European Southern Observatory (ESO) helped him get set up and happened to introduce him to Don Tomás Poblete, who owned a fruit farm near Santiago. (In the early 1900s, Poblete's father had emigrated at the age of 12 from southern to northern Chile, newly acquired from Peru and Bolivia, and made his fortune selling produce to the mining companies.) Poblete never lost his love of the northern desert and had built a home in San Pedro de Atacama—and a comfortable adobe hotel on his property.

"In a country of charming people, Don Tomás and his wife, Milka, and son, Jorge, are five standard deviations above," says Readhead. Poblete offered to build an apartment for the Caltech astronomers at his hotel. When he unveiled the CBI headquarters (five bedrooms, two computer rooms, and a kitchen) in August 1999, "it was fantastic," says Readhead. It was half again as big as had been contracted for, and "every room was a bigger surprise. Don Tomás told us he asked himself 'What would *I* want if I were to stay here for two years? And this is what I've built for you.'"

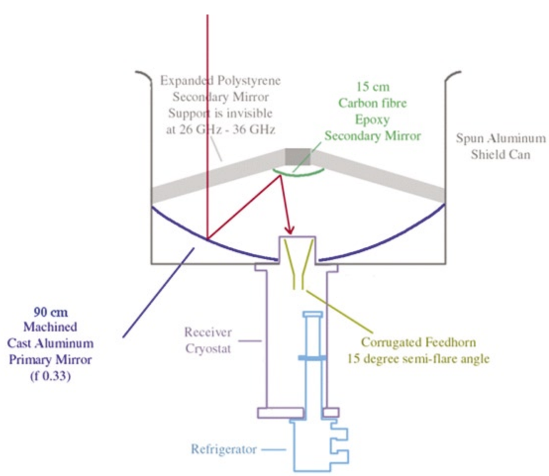
When a few local people (impossible to put on the distant Caltech payroll) needed to be hired, Poblete took them on as employees of his hotel. The Casa de Don Tomás is probably the only hotel in the world with telescope technicians on its payroll. Poblete remains close to the project and still showers the astronomers with hospitality and assistance. "San Pedro is the last dream of my life," says Poblete, who believes that what the astronomers have brought, especially knowledge, is good for the village. "Your dreams are my dreams," he told them.

The Cosmic Background Imager was crated up to leave Caltech in July 1999, arriving in Chile in August. By October, the telescope was at the site, snug inside its dome, its generators humming (sometimes). By January it was ready to go to work.



Above: One of the 13 antennas in its aluminum shield can, which is diagramed below.

Far right: In the on-site lab, University of Chile grad student Cristobal Achermann and local technician José Cortes repair one of the refrigerator units which keep the receivers at -450° F.

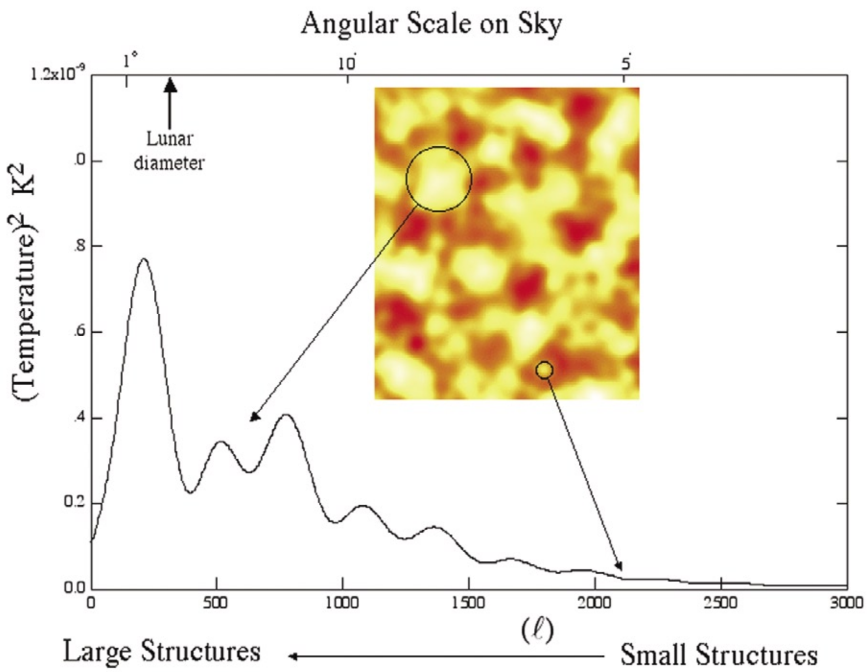


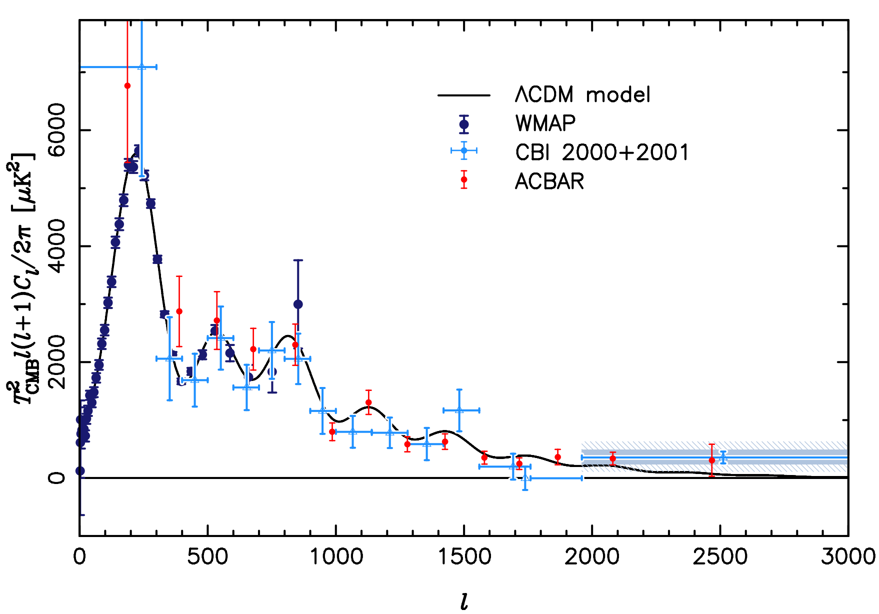
The CBI is a millimeter-wavelength radio interferometer, the first in Chile, and consists of 13 antennas arrayed on a platform 6 meters in diameter. Each 0.9-meter antenna has its own receiver, sheltered by a shield can to prevent cross talk from leaking between its neighbors. Although it's tiny compared to the 40-meter antenna at Caltech's Owens Valley Radio Observatory (OVRO), "it's a very powerful instrument," says Readhead, 75 times more sensitive than the 40-meter for this particular kind of work. Each of the 13 antennas can be paired with any of the 12 others, and the signals from the 78 possible pairs at 10 different frequencies multiplied and correlated to act as an array of 780 interferometers.

Steve Padin, the team's chief scientist, designed the complex correlator (which correlates the signals from each pair forming an interferometer) and much of the other instrumentation. Readhead describes him as a "world-class instrumentalist" and calls Tim Pearson, senior research associate, who was responsible for the data-reduction and analysis software, "one of the best writers of astronomical software in the world." Also among the original group were staff scientist Martin Shepherd, "a truly outstanding programmer," who designed the computer-control and data-acquisition systems; John Cartwright (PhD '03), who built the amplifiers that determine the telescope's sensitivity and carried out pioneering polarization observations for his thesis; grad students Jonathan Sievers (PhD '04) and Patricia Udomprasert (PhD '04); and engineers Walt Schaal and John Yamasaki.

Because the receivers need to be kept at about −450° F (6 K, or degrees above absolute zero), closed-cycle helium refrigerators are an essential part of the design and a continual challenge to maintain. When a "fridge" breaks down, you can't just call in someone from Atacama Appliance Repair. In the first years, the fridges were sent all the way back to the U. S. for maintenance, but now the local technicians and grad students, equipped with the equivalent of a private machine shop and hardware store (from nails and screwdrivers to replacement parts) do most of the repairs on the site.

Why do the receivers have to be so cold? They're trying to detect temperature differences of only millionths of a degree (or microkelvins), which indicate density differences in the microwave background radiation. The microwave background was discovered accidentally in 1965 by Arno Penzias and Robert Wilson (PhD '62) of Bell Labs, and was seen as proof that the Big Bang theory of the universe, which predicted such radiation, was correct. Since then, astronomers and physicists have been training their sights on it, with ever more sensitive and sophisticated instruments, to tease out cosmological clues about the embryonic universe—how galaxies and stars were born. Using





Top: The CBI's image of the galaxy seeds represents temperature fluctuations (red represents cooler spots and yellow, warmer) that indicate density differences in the cosmic background radiation. It's an area of the sky 2° across, or about four times the diameter of the full moon. The curve is the temperature fluctuations predicted by the inflationary-universe model, the larger structures at higher peaks and the smaller ones barely above the axis.

Bottom: Two years' worth of CBI observations are compared with other experiments searching the microwave background. WMAP (Wilkinson Microwave Anisotropy Probe) is a NASA/Princeton satellite mapping the whole sky at large angular scales, while ACBAR (Arcminute Cosmology Bolometer Array Receiver), at the South Pole, measures the background radiation at a wavelength of 2 mm, as opposed to the 1-cm wavelength received by the CBI. ACBAR, a UC Berkeley project, has a number of Caltech collaborators.

OVRO's 40-meter telescope in the 1980s, Readhead saw no temperature fluctuations in the microwave background. After writing a paper in 1989 showing that this implied that galaxies would not have had sufficient time to condense unless most of the matter in the universe were "dark matter," he was teased for proving that we didn't exist. Then the COBE (Cosmic Background Explorer) satellite, launched in 1989, became the first to show that the background temperature was not uniform, confirming what had been suspected—that inscribed on the radiation is the cosmic DNA that spells out how galaxies were conceived, as well as such fundamental cosmological parameters as the size, age, and geometry of the universe.

But the Big Bang theory still presented a bunch of problems: Why did the universe expand? Is the expansion accelerating or decelerating? How can it be so uniform in all directions when its components can't communicate because their separation is greater than the time it takes light to travel between them? Inflation theory, which proposes a massive expansion in the first fraction of a second after the Big Bang, offers solutions to these problems. "It may not be true, of course," says Readhead, but data from the CBI and other instruments so far appear to buttress the predictions of an inflationary universe.

One of those predictions is that the universe is very nearly "flat"—not flat in the sense of a pancake, but flat in the sense of Euclidian space in which two parallel lines will never converge or diverge, so that the universe will expand forever. This prediction was proven true a few years ago by Andrew Lange, the Goldberger Professor of Physics, whose BOOMERANG experiment observed the microwave background from a balloon high above Antarctica (*E&S*, 2000, No. 3). BOOMERANG's picture of the microwave background radiation also showed differences in density in much finer detail than that of COBE's map, which resolved features in the sky the size of 14 moon diameters. Lange's detectors could see structures the size of 0.5 moon diameters.

The CBI, however, has much finer resolution still; its most widely separated pairs of antennas can resolve details as small as 0.1 moon diameters. The first CBI data provided independent confirmation of the almost "flat" universe, but what was more remarkable were its pictures of the seeds from which all structures in the universe eventually evolved beginning to condense out of the primordial soup. On the CBI's first night of observation, January 11, 2000, "we actually *saw* the seeds of galaxies for the first time," says Readhead. "We saw what it would have looked like." (Even though this is a radio telescope, the astronomers are seeing what human eyes would have seen. The radiation has been redshifted and stretched to the longer wavelengths of radio waves, but when the photons were emitted, they were the shorter wavelengths of light photons.)

Even rugged four-wheel-drive trucks can find it rough going in the desert or on the rudimentary Atacama roads. And sometimes, when the roads are impassable, a little tow from a friend is welcome.

Seeing the microwave background in such fine resolution made up for the hassles that are inevitable when operating at an unsupported remote site. The power generators have been challenging to maintain in conditions where the temperature can drop to –20° C with winds of over 50 miles per hour and blizzards occur a few times each year. So a lot of effort has to be expended on maintaining infrastructure. "We've had 12 or 15 total losses of power over the five years of operation," says Readhead, "and each time that happens, all 13 of our cryosystems warm up. Although it's clearly not the case, it sometimes feels as though keeping things running is as big a challenge as doing the actual experiment."

"Some people think that astronomy is something that's romantic and fun—looking at the stars at night, you know, and that's it," says optical astronomer Maria Teresa Ruiz, chair of the astronomy department at the University of Chile, whose enthusiastic help has been essential to keeping the CBI running. "Most of the work is not like that. Most of it is hard work, some boring parts, and you have to endure that and have enough inspiration to get you over that so you can get to the fun part."

Radio astronomers in particular have a hands-on culture. Readhead recalls his early days at the University of Cambridge, when renowned astronomer Martin Ryle, who later won the Nobel Prize, invited the young grad student to visit the new One-Mile Telescope. "It was pouring rain. We went down to this basement full of electronics, and water was pouring in. So he turned around and said, 'Come on.' We went up to a little shed, and he picked up a pick and handed me a shovel, and we started digging a storm-water drain right then and there. It was hard work, and after about half an hour or so picking and shoveling away in the rain, he turned to me and said emphatically, '*This* is radio astronomy.'"

Floods aren't exactly a problem in the Atacama Desert, but snow and blizzards at the high altitudes are, and the CBI's sturdy four-wheel-drive pickups, which are more at home in this challenging terrain than in Beverly Hills, have often had to abandon the unplowed roads and take their chances navigating boulder fields. Trucks usually travel in twos in snow conditions, since one must always be prepared to tow the other out. Readhead tells a story of four trucks once getting stuck in the snow before a rescue mission succeeded.

Trucks weren't the only thing to get stuck. "The first blizzard we had up there, the generators stopped, and we couldn't get up to the site for three days. By the time we got through, there was no longer any evidence as to why the generators stopped because everything was melting by then." So when the next blizzard hit on a late afternoon, Readhead and Padin jumped into a couple of trucks and headed up to the telescope to figure out why the generators stopped when it snowed. "The last few kilometers were almost total whiteout, and for the next 24 hours it was a continual blizzard. What we found was that the air filter was getting filled with snow, which then turned to ice, and that the generators had failed because the air filters got clogged with ice. For the next 24 hours (we didn't sleep all night and the next day), we went out to the generators—130 meters from the control room—every hour. It turned out that 130 meters is a long way in a whiteout; we were both very glad that there were two of us up there, because you had to be darned careful that you didn't wander off in a random direction. We would take out the air filter, put in a new one, take the other one back and leave it next to our chillers, which put out a lot of heat. We'd thaw it for an hour or so and shake out all the ice and take it back to the generator. It was blowing and it was incredibly cold.

"Finally Steve figured out that we should block off the main air intake so the air would be drawn into the secondary air intake that passed over various parts of the generator, which would melt the snow before it got to the air filter. We got big sheets of cardboard to put over the primary air filters, but we had to tie them onto the grills because the wind was blowing like crazy. We had our oxygen of course, which was essential. You could just about tie one knot before your fingers got too frozen to tie the next knot. So we were alternating—he would tie one knot while I held the flashlight and then we'd switch. We finally got the cardboard over the air filter and that solved the problem. Then we were snowed in for three days. But it's very safe up there as long as you've got power, oxygen, food, water, and heat."

Doing any kind of work at 16,700 feet requires portable oxygen packs, such as emphysema patients carry, and the CBI crew doesn't hesitate to use them while doing anything requiring physical exertion outside or in the dome, which is open to the thin air. The shipping containers that serve as lab, control room, and sleeping quarters for two have enhanced oxygen, that is, enhanced to the level of oxygen at about 10,400 feet. Lack of oxygen affects one's thinking, and when they realize that their sentences are making no sense, the astronomers reach for their oxygen tanks or head indoors.

For the first two years, either Readhead or Padin was always at the site, with alternating shifts of recruits from Pasadena. Two years is a long time in the desert, where the living is *not* easy, and most of the original staff wanted to go home. And the experiment was originally supposed to be over in two years anyway. But Readhead wasn't done yet; he had much more that he wanted to see out there, and he thought the CBI was still the perfect instrument to see it with and Chajnantor the best place to see it from. At the South Pole, its sister instrument, DASI (Degree Angular Scale Interferometer—a smaller version of the same design, with most key hardware and software elements duplicated from the CBI blueprints), was looking for, and had found, polarization in the microwave background radiation, another feature predicted by inflation theory. If inflation is correct, the cosmic microwave background would have been polarized as light and matter were decoupling, when some electrons were still scattering some photons. Viewing the tiny differences in temperature between light waves aligned in different directions (anisotropies) gives astronomers an idea of the dynamics of matter in the epoch of the microwave background.

John Kovac of the DASI group (under John Carlstrom at the University of Chicago, who, as associate professor of astronomy at Caltech had worked with Readhead in the CBI's early days) had developed some "superb" polarizers, which would also be available to the CBI, now about to be virtually orphaned in the desert. Readhead passionately wanted to look for polarization at the CBI's smaller angular scales and superior site. The Kavli Foundation was interested in supporting the polarization upgrade, but what about staffing? "Then Jorge found us these fantastic engineers," he said.

"Tony was complaining that it was very expensive running the CBI, and I said, 'Why don't you hire Chilean engineers?'" said Jorge May, a radio astronomy professor at the University of Chile, who was among the discoverers of the Atacama site. Specifically he meant engineering *students*, a solution that turned out to benefit all parties. "It's good for our economy," said Maria Teresa Ruiz. "We don't have a lot of technology development in Chile. The CBI is on a very modest scale, but these guys who work with Tony on this instrument—they really are working with technology that is at the edge of what's now being developed.

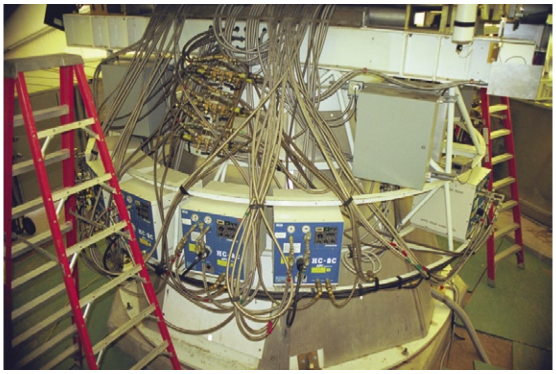
For the polarization experiment, the antennas had to be close-packed in the center of the instrument—so snug that it's difficult to reach into them for maintenance (unless you're very skinny). Compare this with the antenna configuration on page 8.

Right: Preparing for a night of observing, Readhead climbs up to detach a pump that has been pumping down one of the receivers all day. Far right: The cable spaghetti around the instrument's base leads to the receivers and cooling circuits.

And I'm sure eventually they will be able to do things in Chile for companies in different areas of the Chilean economy. Being trained in forefront technology is very important—the way of thinking about things, finding your own solutions. It's that kind of thinking that we need for our country.

"Only the inspirational part of astronomy gets to the general public and to the government," Ruiz continued. "It's not like in biology where you can discover things that are worth money. Other sciences—they all have this practical aspect. There are no patents to be had in astronomy. But what many people have not realized is that there's a lot of technological development that goes on—spinoffs—that can be applied to things that involve some money."

May, who had been an engineer before becoming a radio astronomer, first recommended Pablo Altamirano, an electrical engineering grad student at the University of Chile. In addition, the University of Concepción was particularly open to the idea of a radio astronomy program within the engineering department, and Ricardo Bustos switched from the University of Chile to the University of Concepción for his PhD on the CBI. "They're absolutely superb at diagnosing problems and then fixing them," boasts Readhead. The two Chilean students, later joined by another two (Cristobal Achermann and Rodrigo Reeves), performed the polarization upgrade on the CBI, which involved dismantling the 13 receivers, rewiring everything, and reconfiguring the antennas—moving them from the perimeter to an array (with six adjusted to right-hand circularly polarized radiation and seven to left-hand) in the center of the platform, so closely packed that the engineers and technicians had to become contortionists to get to them. "If the central receiver fails, the only way you can get to it is by worming your way up this cable rack," says Readhead, who isn't eager to try it himself unless he has to. "And if you do the wrong thing you can easily short out the cooling system. Then



Right: At sunset, Achermann unfastens the dome latch, and the clamshell opens behind the shipping containers housing the lab and control room. Below: In the control room, Achermann (background) catches photons, while technician Cortes monitors the various parameters of the instrument's operation. Before coming to work on the CBI, Cortes had never touched a computer keyboard.

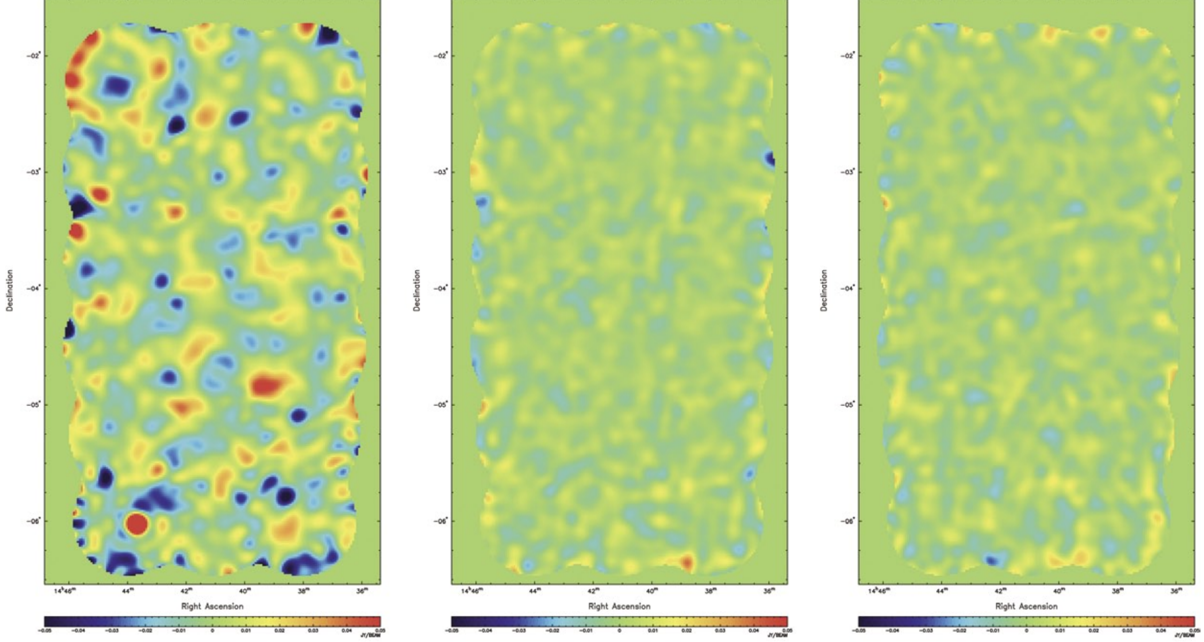
you've blown everything—you've got 13 receivers that are warming up and you've got a big problem on your hands."

Recruiting the Chilean grad students had one unintended consequence. "Tony is so inspiring for these guys," says Ruiz. "These are engineers. But after a year of working with Tony, they all want to be astronomers. They're so important for the project, but now they all want to get PhDs in astronomy. That's *his* fault; he shouldn't be so inspiring."

Still, Achermann and Reeves are sticking closer to engineering and writing dissertations on the instrumentation that they helped develop for the CBI. Currently, the two are alternating time slots for running the telescope—three weeks at Chajnantor and two weeks back at the university. At Chajnantor, they're completely in charge of the project and of running the site. "It's a tremendous responsibility," says Readhead. With help from the San Pedro technicians, they maintain the telescope, including troubleshooting ("I feel like a SWAT team," says Achermann, who describes the telescope as "like a big toy."), and do all the observing as well—the fun part. Another electrical engineering student, Nolberto Oyarce, is the most recent team recruit.

"There's no way we could have done it without them," says Readhead, but the University of Chile has also benefited from this unique arrangement with Caltech. From the beginning, its astronomers have had access to 10 percent of the observing time on the CBI and have been coauthors on most of the CBI papers. The instrument has been ideal for teaching radio astronomy, and students, including undergraduates, have worked there in the summer, collecting and analyzing data. The university had been trying to figure out how to train engineers and technicians to staff all the new foreign telescopes about to arrive in Chile, and the CBI has provided a perfect model, according to Ruiz. Just last spring, the university established a new PhD program in electrical engineering with a major in astronomical instrumentation—a direct spinoff from the CBI project. And that's all in addition to the know-how the students are gaining by working with the polarizers.

With the polarizing upgrade complete, observations began in September 2002. But the search for polarized light—finding anisotropies in already incredibly small temperature fluctuations (smaller by a factor of 10 than previous observations)—took a dogged 300 nights of observing (in contrast to the eureka moment of CBI's first night). Just as polarizing sunglasses transmit only the light that is aligned with the glasses, the CBI's polarizers pick out only the polarized light from the total intensity (including unpolarized radiation). The team observed four patches of sky, all together an area about 300 times the size of the moon. By April 2004, the data were complete enough for the team to be confident that they had indeed seen polarized light, evidence of how the matter condensing into



These recent images cover a patch of sky about 2.5 x 5 degrees, one of four areas the CBI observed between 2002 and 2004. The left-hand image shows the total intensity (unpolarized radiation) of the microwave background signal. The other two images of the same patch map the radiation polarized vertically (center) and at 45° (right) and show that it is much weaker than the total intensity—about 10 percent of it. The polarization signal is also contaminated by noise from the telescope itself, so the CBI astronomers must use statistical analysis to extract the polarization information. (Reprinted with permission from A.C.S. Readhead et al., *Science*, vol. 306, no. 5697, 836-844, © 2004 AAAS.)

galaxies is actually moving. Published in October 2004 as the cover article in *Science*, the work confirms DASI's results and extends them to the higher resolution that can actually see the galaxy clusters. The CBI data also shows that the polarization signal is out of step with the total intensity signal—that is, the peaks of the polarized signal correspond to the valleys of the total signal and vice versa—a sure indication of the motion of the primordial plasma as it falls into the seeds of galaxy clusters, confirming one of the basic predictions of the theory.

Cooperation with other experiments will be essential as the observations become orders of magnitude more difficult. Readhead predicts that what the CBI is doing with its sister instruments is going to lead to a revolution in fundamental physics. Cosmology and particle physics have come together, he claims, cosmology providing the "laboratory" for high energies unattainable in earthly accelerators. "And whenever two scientific disciplines come together and find they have common ground, you get incredibly interesting things going on at the interface," he says.

Things like dark matter. What Readhead is seeing is fluctuations in the dark matter itself—nonbaryonic stuff that is not made up of protons and neutrons, as is all the matter we can see around us. Nonbaryonic matter, which is thought to account for about 22 percent of the energy of the universe (dark energy makes up another 74 percent) would have the much larger density fluctuations necessary to form galaxies in the billion years or so it took to form them. But, because it doesn't interact so strongly with light, it produces the small temperature fluctuations in the microwave background on the scale of galaxy clusters—implied by OVRO's 40-meter telescope back in the 1980s (when Readhead "proved that we don't exist") and finally seen for the first time by the CBI. Readhead describes the ordinary matter of the galaxies as collapsing into "wells" in the dark matter. "So it looks to us as if galaxies are isolated," says Readhead, "but the stuff that has really formed them and caused them to be there is all around them, still touching," even though we can't see it now. He's hoping new detectors will enable him to see it more clearly *then*.

A new type of detector, called MMIC (Monolithic Millimeter-Wave Integrated Circuit) Arrays, is being developed at the Jet Propulsion Laboratory by Todd Gaier, Charles Lawrence, and Mike Seiffert, and will be installed in a new experiment on the CBI platform, called QUIET, for Q/U Imaging ExperimenT. The 1,000-element array, the first radio "cameras," which will improve the CBI's sensitivity to a fraction of a tenth of a microkelvin, should be ready in 2006. A second string to QUIET will be the importation of a new 7-meter telescope to complement the range of angular scales observed with the upgraded CBI. Readhead, who considers himself lucky to be working at a time when so much new technology is constantly coming on line, likens it to a new window that has opened. "You don't know what you're going to see through that new window," he says, which is exciting to an astronomer but hard to explain to funding agencies.

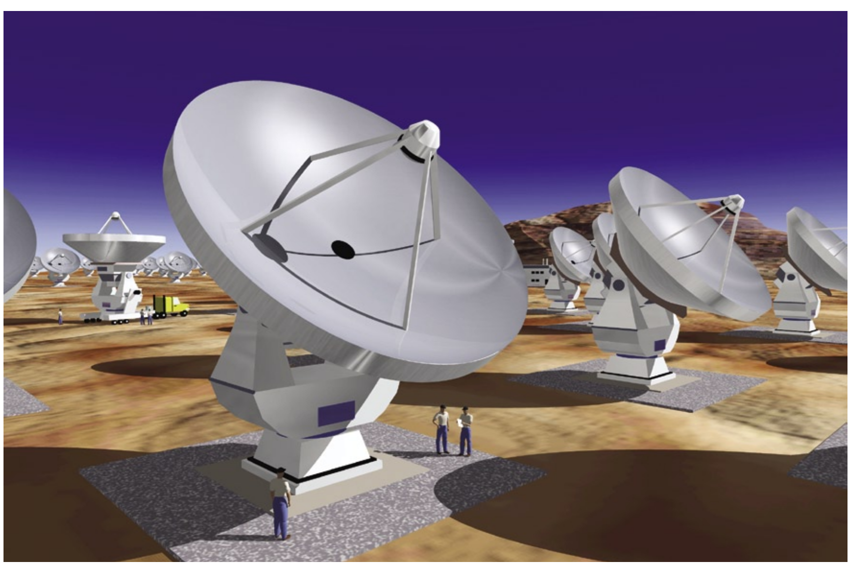
Readhead is hoping for NSF funding next year for QUIET and hopes to make the Chajnantor Observatory a permanent Caltech facility. While the project has received most of its support from NSF, more than 40 percent has come from Caltech. Besides the two Chilean universities, the Canadian Institute for Advanced Research, the Kavli Institute for Cosmological Physics at the University of Chicago, and the National Radio Astronomy Observatory have collaborated on the CBI. In addition to the Lindes' founding gift, Cecil and Sally Drinkward gave to the project, and continuing support has come from Barbara and Stanley Rawn, Jr. The Rawns most recently have provided funds for a Caltech graduate student and a postdoc; Clive Dickinson (the most recent recipient of the Michael Penston Prize for the best astronomy or astrophysics thesis in the United Kingdom) arrived last summer from the University of Manchester to take up the latter post. And some members of the Associates on a President's Circle trip to Chile last year, were so impressed with the CBI's well-run organization (as well as with the science) that they offered substantial contributions on the spot.

The Cosmic Background Imager is no longer alone on the Chajnantor plain. ASTE (Atacama Submillimeter Telescope Experiment) arrived at the Pampa la Bola, just below Chajnantor, in 2002, and its Japanese scientists are now sharing Don Tomás's suite with the diminished Caltech crew (although the fastidious Japanese maintain their own pristine refrigerator, separate from the sloppier American/Chilean group). APEX (Atacama Pathfinder Experiment), a German-built antenna, is just coming into operation. A Caltech/JPL/Cornell collaboration is surveying a nearby peak as a site for a 25-meter submillimeter antenna, as is Princeton for ACT (Atacama Cosmological Telescope).

But what will alter the landscape the most is ALMA (Atacama Large Millimeter Array), a massive American-European-Japanese undertaking, scheduled to join the CBI in 2008. No less than 68 twelve-meter telescopes (plus 12 seven-meter ones), of which APEX is a prototype, will mushroom across Chajnantor. There will be a paved road (ALMA has already graded a better dirt road across the plain) and a reliable source of power; Readhead's Chilean proteges will have plenty of job opportunities; and the astronomers in San Pedro de Atacama may well outnumber the tourists and the ubiquitous local dogs.

Ruiz and some ALMA staff met not long ago with some of the local farmers and villagers about the changes that are coming. "I gave them a talk," she says, "the same talk I give to the general public about the evolution of the universe, with pictures and everything. And then representatives from ALMA gave short talks about what they would do there—how they would operate and how they would create new jobs, because they will need people to clean and cook and things like that. So then came the question time. And this guy raised his hand and he said, 'More jobs is very good news because we need jobs in this area, but it is not the most important thing. The most important thing for us is our kids, and we would like to know how you can help us get a better education for them so that they can become astronomers and do all of these discoveries that this lady is telling us about.' I thought that was fantastic," says Ruiz.

A big family is moving in next door. Over the next three years, ALMA (Atacama Large Millimeter Array) will plant 80 antennas on the Llano de Chajnantor. A multinational undertaking, it will be the world's largest millimeter-wavelength telescope. (Artist's rendering courtesy of the European Southern Observatory.)



Readhead hopes that CBI/QUIET will still be there, probing the cosmic background radiation for more clues to the nature of dark matter and dark energy and also, as the instrument's sensitivity increases, opening up new areas of study in the radiation from our own galaxy. He and his collaborators have already discovered a new form of "anomalous" galactic emission that is not understood, and he already has plans for what should come next.

Throughout the CBI's existence, Caltech's president, provost, and the division chair of physics, mathematics and astronomy have supported it strongly. Recently, new collaborations with the Jet Propulsion Laboratory, with the English universities of Oxford and Manchester, and with the Max Planck Institute for Radio Astronomy in Bonn have brought additional support, as well as ideas for novel instrumentation. A lot remains to be learned from the cosmic background radiation, and this ground-based site can accommodate larger, cheaper instruments than can be launched into space, such as European Space Agency's Planck satellite, scheduled for 2008.

The future of the observatory will depend on continued innovation in a very competitive field, as well as continued support from NSF and generous private donors, but Readhead is confident that the importance and excitement of the science, the potential of the new instrumentation, and the extraordinary quality of the atmosphere at the site will ensure its survival.

Readhead remembers what it was like as the lone settler on Chajnantor. "It's wonderfully romantic when you're the only one on that site and you're up there observing," says Readhead. "That's one of the things I like the most—to be up there observing on my own." Life will be much easier now (easy might trump romantic), and Readhead welcomes all his imminent new neighbors, as the CBI continues to push the latest technological developments to the limits of what is achievable from the ground. □

PICTURE CREDITS: 8, 10, 11, 15–Jane Dietrich; 13–José Cortes