Our Universe:

The Magnetism & Thrill of Extragalactic Exploration

As Described by Leading Astronomers

SO WE'VE LOST THE MISSION?
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The Big Bang and the Cosmic Background Explorer

Two days after the Cosmic Background Explorer satellite was launched, my wife heard me answer a 4:00 AM phone call with the words "So we've lost the mission?" COBE had lost a gyro and we didn't know how well we would recover. Needless to say I got up, only an hour after getting home, to see what could be done. Fortunately, all would be well, and only a few weeks later, our team announced to the American Astronomical Society that the Big Bang theory was in good shape too.

We had proposed the COBE back in 1974, when I was only a few months out of graduate school, and now, 15 years later, all our dreams had gone into space, riding a rocket on a pillar of smoke. I will tell the tale of how the project got started, how a country nerd ended up standing in a dark field by the seacoast at dawn watching the launch, how it affected my life, and how it opened a new field of astronomy.

We built the COBE to look at the beginning of the universe. Until 1929, only theologians and philosophers thought that the universe even had a beginning. Scientists had almost no evidence. That year, the year of the great stock market crash, was also the year that Edwin Hubble discovered that distant galaxies are receding from us. Not only are they receding, but the farther away they are, the faster they are going, in exactly the pattern they would have if they were all debris from some cosmic explosion. Einstein had said it was impossible, believing without any observational evidence that the universe could not be expanding, and told the Belgian abbot and scientist Georges Lemaître that "your calculations are correct but your physics is abominable." Einstein had previously introduced an extra term, the famous Λ constant, in his general relativity formulas to allow the universe to be stationary. Nevertheless, the universe does expand, and Einstein later admitted that his mistaken belief was the greatest mistake of his career. Curiously enough, the Λ constant is back in favor as a cause of an early rapid expansion, and it may be causing the expansion to accelerate even today.

Then, science took a break from fundamental research, and went to work in service of war, inventing radar, jet aircraft, and atomic bombs. In the late 1940's, as the world recovered, Ralph Alpher was a graduate student, and Robert Herman had just gotten his Ph.D. They were working with astronomer George Gamow to think about the early universe. The three predicted that the expanding universe must have had an extremely hot beginning, and computed the amount of hydrogen and helium that should have been produced by nuclear reactions in the primordial soup. They also predicted that the universe should be filled by the residual heat radiation of that time, now reduced to a temperature of a few degrees above absolute zero. This radiation, now called the cosmic microwave background radiation, would be recognizable because it should come to us with the same brightness from every direction. It would have been difficult or impossible to measure with 1940's technology, even though it was predicted to be as bright as starlight. By 1950, the debate about the nature of the universe was very public, and the British Broadcasting Corporation carried it live. Fred Hoyle, putting down the idea of the hot beginning, called it the "Big Bang," with full British innuendo, but the name stuck. Not much could be done to test the idea at first. The theory was worked out more completely, but the real breakthrough happened in 1965. Arno Penzias and Bob Wilson, working at the Bell Telephone Labs in New Jersey, discovered the microwave radiation, as they tested out some new receivers for the Telstar communications satellite. There it was, loud and clear, and suddenly the world of cosmology was different. Hoyle's Steady State Theory had failed to predict the radiation, and the Big Bang theory reigned supreme.

Curiously enough, Penzias and Wilson hadn't read George Gamow's popular books about the Big Bang, they hadn't read the original 1940's papers by Alpher, Herman, and Gamow, and they didn't know what they had found. Just down the road in Princeton, four people were looking for the radiation on purpose, and when they heard about the Penzias and Wilson results they immediately knew what they meant. They confirmed the discovery quite soon, but they hadn't read the books and old papers either. There's quite a tale there, of pride, social status, and credit for discovery. In retrospect we know of many missed opportunities going back to the 1940's. Penzias and Wilson got the Nobel Prize.

Growing Up Nerdish

I started out as a child, as Bill Cosby said. Back in 1953, Mars was very close to Earth, I was 7 years old, and my parents took my sister and me to the Museum of Natural History in New York City. We saw the giant meteorite at the Hayden Planetarium, we saw the model on the ceiling with the planets circling the Sun, we heard about canals on Mars, we saw the dinosaur bones stamping their feet, we saw the evolution displays of fish and human ancestors, and I was hooked. I wanted to know how we got here, from the beginning. My father studied dairy cattle breeding and feeding at the Rutgers experiment station in Sussex, New Jersey, and he told me bedtime stories about cells and genes. My mother was a grade school teacher and she read out loud from biographies of Darwin and Galileo. Her father was a bacteriologist at Abbott Laboratories, and had helped develop penicillin. Scientists were heroes, and sometimes in great danger. I read Paul deKruif's "Microbe Hunters," and thought about making the world a better place through science. I had nightmares about being imprisoned for my beliefs, or for teaching evolution in the schools.

I was only 11 when the Sputnik went up. Americans were already afraid of the Russians, and now we were desperately afraid. We had air raid drills in school, and were taught how to put our heads down under our desks. My father got a Geiger counter to find out if things were radioactive, and was part of the Civil Defense system. Suddenly it was good to be good at science and math. I got books every two weeks from the Bookmobile, which the county library sent around to farms. Even the library itself was brand new.

We had a science fair, and I saved up my allowance, a quarter a week for a long time, to buy a Heathkit short wave radio with 5 vacuum tubes. I put it together myself, but it didn't work because my soldering iron was meant for roofing, and had melted some parts. A few months later I found out how to get some new parts, and suddenly there were voices from far away. I studied the parts catalog from Allied Radio the way other kids memorized baseball statistics. I built a "robot" with some vacuum tubes and motors from my Erector set, and entered it in the science fair, but it didn't do anything. Transistors were invented, and Boys Life, the Boy Scouts' magazine, carried articles about how to build radios. Microwave relay towers were built on the mountain nearby, and one of the engineers there started up a 4H club for electronics.

By the time high school came around, the country was supporting summer schools for science kids. I learned math at Assumption College in Worcester, Massachusetts one summer, in an old red brick building whose cupola had been touched by a tornado while people were praying inside it. I learned physics at Cornell University the summer between my junior and senior years in high school, and now I thought I might really be able to be a scientist. I'd seen some labs and I loved the energy of my favorite teacher, Mike Nieto, who was a grad student. I was even pretty good at the work. I got back to telescopes, saved up my allowance, and assembled a small reflector from parts from Edmund Scientific. I borrowed "The Amateur Telescope Maker," all three volumes, from the library over and over. I tried to measure the motions of asteroids and compute their orbits, but the math was much too hard for me. I tried to learn it from a book, but Gauss, who invented this subject in the mid 19th century, was way ahead of me (and still is). I did enter this project in my high school science fair, and it went on to state level and won me a trip to Chicago and an invitation to go on a Navy cruise.

College and Grad School

College was quite a challenge. I went to Swarthmore, warned by my parents that I'd been a big fish in a little pond, and I would have to study very hard to win again. I did, and it worked. I was keenly aware that they were paying for me to go, and I was determined to get every bit out of it. From there it was off to Berkeley for graduate school. That was a much bigger pond, and a real shock. Swarthmore was a little school, only 1200 people in a small town. Berkeley was huge and at least the physics students weren't very social. They'd come in to class and sit down with their books and read. The psychology students went to class and planned their adventures and their parties. After a couple of years of taking classes and going to the library, I was pretty tired of school. Then came my lucky break. It was time to find a research topic and a research professor, and I met some wonderful mentors. Paul Richards was my thesis advisor, and in his labs I worked on designs for instruments to measure the cosmic microwave radiation. Mike Werner had just received his Ph.D. and was working in Charles Townes's group, and they taught me a lot too. It was 1970, just five years after the radiation had been found, and the news from a rocket experiment said that the Big Bang theory wasn't right. The radiation was 50 times too bright. Worse yet, a mountaintop experiment said that there was a spectrum line in the cosmic background radiation, a frequency where the radiation was much brighter than at nearby frequencies. The Big Bang couldn't do that, so maybe the radiation wasn't cosmic after all. We ought to check.

It took us a long time. First, we built a new instrument to take to White Mountain in California. It was called a Fabry Perot interferometer and it was really tricky, especially for our first effort. I worked with Mike Werner on this project. We helicoptered ourselves and the apparatus up the mountain in the winter and tried to breathe. At first our fingers and tongues were blue from lack of oxygen, but after a few days the headaches went away and our color came back and we could think a little again. After two trips we concluded there was nothing wrong with the big bang radiation that we could see. Alas, our ability to measure the cosmic radiation was limited by the air overhead, which emits its own radiation.

Our next adventure was to Palestine, Texas, a small town south of Dallas where scientific balloons are launched. Our new apparatus hung by thousand-foot cord from a huge polyethylene bag, as big as a football field. It would do a better job than we could manage from the mountain, because it would go above 99.5% of the air. This new project took until 1973 to get ready. We got impatient. More tests would take a long time, and they wouldn't be very realistic. Maybe the apparatus would work. We (my fellow grad student David Woody and I) drove it to Texas on a yellow University truck, across the Arizona and New Mexican deserts to the lush greenery of watermelon fields of East Texas. We launched it, or I should say a lot of people launched it. The crew to handle these huge things is very professional and they have the most amazing equipment. Tiny Tim, a converted earth mover, dangles the payload from his huge jaws 20 feet in the air, while the balloon bag rises overhead, and then races across the field with it until the cable pulls tight and the balloon lifts our work into the sky.

Well, it didn't work. It didn't work for three different reasons, which we found out after we got back. That night was awful. Three years of work went up, up, and away, and there wasn't a thing we could do about it. We sat in the control room, thinking about what to do to recover, and sending computer commands, but nothing helped. It was a defining moment. I decided that my Zen needed revision. I couldn't, I wouldn't ever, be so impatient. I would test everything. This time, Paul let me finish my thesis on the basis of the previous work, and in January 1974 I left California for a new life. David rebuilt the apparatus and flew it again three times after I left, and it worked twice. The measurements said the radiation had just the right spectrum to match the predictions, and the Big Bang theory was still OK.

Going to Work for NASA

I would be a radio astronomer. Pat Thaddeus in New York City, at NASA's Goddard Institute for Space Studies, had just built a new telescope on the roof of the physics building at Columbia University. I wanted out of cosmology. I wanted to do something where it didn't take years to build the apparatus and then see it fail. Pat got me started observing with a radio telescope and making some computer calculations, and I even made a little progress. However, the fates had something else in mind. NASA. NASA had sent around a team to Berkeley to see what their Space Sciences Lab there was doing, and I had told them about our balloon project. They wanted to know why we weren't doing it in space. I thought, "Who, me, I'm just a kid?"

So in summer of 1974, NASA issued a nationwide call for satellite proposals. Pat said we should all think of ideas. There was only one thing I knew anything about, my ill-fated thesis experiment. By now the emotional sore spots had worn off and I thought maybe it was worth doing in space. It could be done thousands of times better than we could imagine doing even with a balloon. Pat said I should call his friends and assemble a team, so I did. Six of us wrote a very thin proposal for the "Cosmological Background Radiation Satellite," and sent it in. We wanted to build four instruments, three of them inside a tank of liquid helium, and put them in space.

We had three objectives. First, we would measure the spectrum of the cosmic background radiation a thousand times better than we had done with my thesis experiment, and compare it directly with a nearly perfect blackbody. A blackbody is an object that absorbs all radiation that falls on it, and it is also a perfect radiator whose brightness follows a simple formula. If the Big Bang theory is right, the background should match a blackbody at a particular temperature, which we would measure. Second, we would look to see if the microwave radiation is equally bright in all directions, as it should be if it comes from the Big Bang, and then we would look for little hot and cold spots that might be the seeds for galaxies and clusters of galaxies. Third, we would look for the light from the first galaxies. Maybe the early universe is filled with galaxies that are too far away for any telescope to see them, but we might still find the hazy glow.

I drew a picture and a draftsman tidied it up (this was before computers could draw). In retrospect it amazes me that so much could come from such a little booklet. Now, in today's intensely competitive environment, such a short proposal would have no chance, but in those days most proposals were about as thin as ours. I have to think we had a guardian angel, and it was true, we did: Nancy Boggess was at NASA Headquarters, and she was a strong advocate of the new field of space infrared astronomy. Also, major scientific advisory committees had told NASA that our subject was very important.

In reality, though, our fate was to compete with over a hundred other proposals. Two other groups had put in ideas related to ours, one from Berkeley, and one from the Jet Propulsion Laboratory in Pasadena, California. At first, NASA thought one of our instruments (the one most like my thesis experiment) might go along with another mission that wanted a helium cryostat, but that turned out to be much too difficult. Instead, NASA formed a new team from members of our group and the Berkeley and JPL teams. We would figure out what to do now. In 1976, I took a job at NASA's main science lab, Goddard Space Flight Center in Greenbelt, Maryland, in hopes that our new project might become real. If the project were selected, I would be its lead NASA scientist, and I would be in charge of one of the instruments. Suddenly I was the center of a whirlwind. Be careful what you ask for, you might get it! I was 30 but I still felt like a kid, a bit awkward with words, and when I had to give a speech for the first time I got cold sweat running down my back. Maybe it was a good thing that I didn't know to be afraid of what I was getting into.

Now we had a chance. NASA sent the twelve winners of the first round of competition a little money to support writing a more complete proposal. We sent our bit out to our team members and to Ball Brothers in Boulder. Ball Brothers spent a lot of their own money too, in hopes of winning some contracts when the competition was over. We wrote a very thick proposal this time, two volumes each an inch thick. It demonstrated we could do this mission within the allowed budget, and it would measure the Big Bang radiation and look for the radiation from the first galaxies. We even decided on a new name, the "Cosmic Background Explorer," or COBE. Review committees smiled upon it. NASA gets external advice from scientists around the country, and they apparently felt that the obvious difficulty of the work was still acceptable because of the tremendous importance of the results we might get.

Building a Team

So Goddard Space Flight Center built us a team. The International Ultraviolet Explorer was just getting completed (it operated successfully for 18 years before it was turned off), and their management took us under their wing. They knew how to do things, and they had a working organization. Would we build the equipment at Goddard, or would we buy it? I was nervous about buying it, because nobody knew what to buy. Nobody had ever designed anything like what we wanted. Ball was good, but they hadn't built these instruments either, and they were getting expensive as they realized what it would take to do the job. They were building a cryostat (the liquid helium tank we would need) for another project, so we planned to buy another one from them. The instruments would be so far beyond what anyone had done that many good engineers thought it was impossible. They were almost right. We didn't know how to do it at Goddard either, but at least the scientists and engineers could work together there. If we bought from a big aerospace firm, I was afraid we'd be talking to lawyers and accountants instead. In the end though it wasn't a matter of principle, it was cost. Goddard adopted us. It would contribute manpower, and it wouldn't come out of the budget. The engineers wanted something so challenging that they could use it to attract good new talent. There was just one string attached. Other projects had priority. If company X made a big mess of the work NASA was paying for, NASA had to pick up the pieces and make things right.

So we fought, politely. Our team wanted the best engineers, but so did everybody else. Our team wanted priority in the shop. So did they. Worse than that, Goddard (like many engineering companies) has what's called a "matrix organization," in which everyone has multiple bosses who argue over who works on what. The matrix organization would be the death of us as we tried to claim our percentages of time from each person. It wasn't working. The only thing that broke the logjam was a national disaster. In January 1986, the Challenger exploded. Nothing would bring back the dead astronauts. Other rockets exploded in the ensuing months, both American and European. Things looked extremely grim everywhere. National pride stepped in, and people refused to let NASA die too. Congress gave money, and NASA would build another Shuttle. But what would COBE do in the meantime? COBE was going to ride on a Shuttle, and so was practically every other NASA payload. That was the bargain with the White House and the Congress. So, we were stuck.

Recovering from Disaster

Dennis McCarthy, our Deputy Project Manager, found a way. He talked to other countries about partnerships for COBE, in which they could provide a rocket to go with Goddard's spacecraft. NASA Headquarters heard about it and threatened terrible things. NASA would have to find a way to launch COBE with American rockets. How could American pride be maintained if COBE went on a foreign rocket? The very thought was appalling. Dennis found the way. There were parts for an American Delta rocket, and there might be enough to build a whole one. The COBE, which weighed 10,500 pounds loaded with fuel, might be shrunken to 5000 pounds, the maximum the Delta could put in our orbit. In a few months, we had a plan. We would launch in early 1989, and we would have top priority. We would be NASA's first science mission after Challenger, and America would be proud. We would make a "skunk works," named after the famous Lockheed facility where spy planes were built for the Cold War, and we would bring together the key team members in one place. Nobody could stop us now, and we could insist on immediate results, and overtime (lots of it).

Needless to say, two years was a short time to finish the project when we had to build a whole new spacecraft! We built two of them to make it faster, one to be tested on the shaker and one to fly. The shaker could make 35,000 pounds of force to simulate the launch, and it was a frightening sight. We worked nights and weekends most of the time. Families wondered where we were and when we would ever be done. Vacations were deferred, sometimes for years. We had to keep the instruments extremely clean, so we would be sure we were seeing the beginning of the universe and not just dirt on the mirrors. Some of us spent months in the clean rooms wearing white bunny suits with masks and gloves. We built a "car wash" to clean the parts, and we had several people there round the clock to do it. We no longer had time to make things better. We just did what we had to do, and we only fixed things if we had to. Voltaire said "the better is the enemy of the good," and our team believed it. Even scientists like me had to give up some cherished hopes. Better detectors, more calibration tests, more software and computers, we gave them up.

One night I woke up in a cold sweat. I had just realized that I had designed a fatal flaw in the calibrator for the spectrometer, the instrument for which I was responsible. The next morning I called for help, and after careful calculation we found a solution. It needed more thermal blankets, and it would be cold enough after all. We put the spectrometer together, and it worked. Then we put in a better mirror mechanism, and this time it didn't work. A tiger team was formed, and we found out what we had done wrong. It took just a year to build a new one and put it in.

After we had the whole payload together, in spring of 1989, our engineers insisted on a new test, one in a different orientation. We can't simulate zero gravity on the ground, but we can set up the equipment so gravity has the least possible effect. This time, we tested the calibrator by making its pivot axis vertical, so gravity wouldn't make it swing. The calibrator failed the test. It wouldn't stay in place without the help of gravity, and it wouldn't work in space. We pretty quickly knew what was wrong, and we were lucky. We could fix it without taking everything apart. Another few months and we were ready to ship the payload to California.

It rode down the Capitol Beltway on a special, very slow moving big truck at dawn, and went to Andrews Air Force Base. There, the truck drove onto a giant C5-A aircraft, and flew all the way to California's Vandenberg launch site. There, the truck drove back off, the COBE parts were tested again and reassembled, and the whole thing readied for the top of the Delta rocket. Everything seemed OK. Then, the October 1989 earthquake came, the one that leveled highway bridges in San Francisco. We were hundreds of miles down the coast, and the payload might have been hurt, but luck smiled on us. The delicate mirror mechanism was safely bolted down that day because the two engineers who might have been testing it had taken that day off to get married.

Launch

Finally came the readiness reviews. Was the rocket ready? The parts had been brought back from the graveyard because the Delta production line had stopped years ago, and some fuel tanks had to be patched where pigeon droppings had eaten holes through them. We heard that a wet rag had been left in a pipe during a welding operation, but the pipe was tested and the rag was retrieved. It's impossible not to make mistakes, so it's essential to catch them and fix them. One might say luck was with us, but this one wasn't luck, it was a test procedure based on long hard experience. Of the nearly two hundred Delta rockets before ours, only four failed. On the last day before launch, the rocket guidance computer had to be replaced. Were we supposed to take this as good luck or bad luck? How could we know? Everything was as ready as we knew how to make it, but we all knew that there was no way to tell if it would work. What about all the mistakes we didn't catch? The only way to know was to push the button.

So that's how we came to have 1500 people standing in the fields around the launch site in Lompoc, California at dawn on November 18, 1989. In the daytime, the flat spots were beautiful with commercial flower growing, and the hills are steep and covered with grass and live oaks. In the early morning, before dawn, it was cold and dark and windy and we shivered. The balloons were sent up to find out about the wind above us. At first the wind was too strong, but then it slowed down just enough. A strong wind would blow the rocket off course, and when the rocket nozzles swiveled to compensate, the sideways forces could destroy the rocket. When the button was finally pushed, we were miles from the rocket, and the light came to us long before the sound. At first slowly, then faster and faster, the pinpoint of light climbed to the sky and disappeared. The wind wound the exhaust trail into a pretzel shape near the Moon, the rising sun lit it up, and it was spectacular. The wind had almost destroyed the rocket, but not quite.

Parties, Champagne, and Science

Now was the time for parties and champagne, and for heading back to Goddard to run the spacecraft and turn on the instruments. Within minutes the rocket was out of range, and we wouldn't hear anything from it until it came in range of the ground stations on the other side of the world. Each orbit took 103 minutes. Back at Goddard the next day, I learned that all had worked well, everything was as expected. Then the gyro failed. Fortunately, we had six, and we needed only three. The spacecraft was a bit wobbly, but it was alive, so we learned how to run with a dead one and continued on.

Just a few weeks later, on the second Saturday in January in 1990, we presented our first results to the American Astronomical Society in a giant hotel ballroom in Alexandria, Virginia, near National airport. I was worried that our event was on Saturday, and thought everyone would have gone home already. All of us were totally exhausted, having stayed up to all hours to make the instruments work and learn what they were showing us. I was amazed to see a packed auditorium, well over a thousand astronomers. Nancy Boggess, who had backed us for years at NASA Headquarters and was now working at Goddard with me, gave an introduction. Mike Hauser and George Smoot, the lead scientists for the other two instruments, gave their talks, and I gave mine. I showed a spectrum from the Far Infrared Absolute Spectrophotometer instrument (FIRAS). The plot showed the brightness of the cosmic microwave background radiation at all wavelengths from 0.5 to 5 mm, and it matched the theoretical prediction exactly. I said very little, just projected the plot on the screen, and there was a standing ovation. Everyone knew what it meant, and why it was so important. I was absolutely unprepared for such an outpouring from my colleagues, and could barely say that it was now time for the next speaker. The Big Bang theory had withstood a great test, and it was fine. The COBE team had also withstood a great test, and we were fine.

We found that the cosmic background radiation has a temperature of 2.735 ± 0.06 kelvin, just a little above absolute zero, and that the difference between the measured spectrum and the perfect blackbody was less than 1%. Nothing anyone could imagine but the Big Bang could make such perfection, so the Steady State theory now had a stake through its heart, despite the persistent efforts of Fred Hoyle and his colleagues to resurrect it by improving it. Eight years later, after all the data were analyzed and calibrated, we could say the radiation is even more perfect: 2.725 ± 0.002 K, and only 5 parts in a hundred thousand difference between the cosmos and the perfect blackbody. The answer was 20 times better than we had dared to hope.

Two years later in April, we announced another breakthrough. Our second instrument, the Differential Microwave Radiometer (DMR) had mapped the sky, looking for hot and cold spots in the microwave radiation, that might give some clue about the Big Bang. Sure enough, they were there, but they were extremely faint. These hot and cold spots were only a part in 100,000 different from the average temperature. George Smoot, who was the lead scientist for this instrument, got a lot of publicity for saying it was like looking at the face of God. He wasn't the first to use that phrase, but it brought a huge wave of public attention, and controversy. Religious folks wanted us to agree that our results supported their versions of history. I was interviewed for a Catholic religious TV channel, and our findings were written up in Japanese and Arabic, and reported around the world. George got an offer to write a book for a huge sum of money. The Vatican Observatory (yes, the Pope supports cosmology) held conferences, and Galileo was rehabilitated around then. Scientists wrote thousands of papers citing and interpreting our results, and the maps and the spectrum plot are now in virtually every astronomy textbook.

These hot and cold spots show the universe as it was about 300,000 years after the Big Bang. That's the moment when the hot gases of the Big Bang cooled down enough to become ordinary hydrogen and helium. Before then, the gas was ionized and opaque, and afterwards, the gas was transparent and the primordial heat radiation was free to go in a straight line. According to computer simulations, the hot and cold spots are responsible for our existence, because they were the primordial seeds around which galaxies and clusters of galaxies would grow. The search for more information about these seeds is still a very hot topic, with dozens of projects around the world, one space mission (the Microwave Anisotropy Probe, MAP) being built at Goddard for launch in 2000, and the Planck mission being planned in Europe for launch in 2007. With luck, we'll know how long ago the Big Bang happened, how much matter there was, of both normal and "dark" varieties, and whether the expansion is slowing down or speeding up.

Our third instrument, the Diffuse Infrared Background Experiment (DIRBR) finally yielded its secrets in 1998. Mike Hauser's team found the light from the first galaxies, and it's much brighter than most of us expected. Apparently more than half of the starlight from the early times was absorbed by tiny dust grains and converted into infrared radiation, so we would never have known about it with normal telescopes operating on the ground. This is one of the great surprises of science. Theorists had told us what to expect about the spectrum and the hot and cold spots, but they didn't tell us this one. Now, big telescopes on the ground are beginning to work at some of the wavelengths where these galaxies can be seen, and space missions are being planned to look at them without the interference of the atmosphere. A whole new domain of science is now open, and we know there's something important to find!

Some people think the end of science is near, but I don't. The world is dangerous. The threat of war, terrorism, plague, and natural disaster of all sorts is very strong, and people are investing in technology to protect themselves. Astronomers have benefited from generations of technological advances, and despite the end of the Cold War, there's no reason to think that will stop. There's also no end in sight for what computers can do for us, and I think they'll be a great help. Moore's Law says that computers double in speed and memory every year or two, so how long does it take before they are so powerful that they do things we would never dream of today? This isn't a government bureaucrat's project, it's the response of the marketplace to opportunity. (By the way, the Internet and the Web were invented by Government scientists in the US and Europe, and then made public.) Maybe one year I'll be able to walk into my office and say to my computer, "Hey Nerdina, I think Congress might be ready to approve of a new telescope 30 meters across. How would you build it?" I'm already working on the Next Generation Space Telescope (NGST), a successor to the Hubble Space Telescope that would be 8 meters across. The NGST would be capable of seeing those first galaxies that formed after the Big Bang and maybe produced the infrared radiation that Mike Hauser found. I don't have Nerdina to help yet, but maybe next time...

Suggested Reading

"The Very First Light," John C. Mather and John Boslough, Basic Books, 1996.

"The Next Generation Space Telescope, Visiting a Time When Galaxies Were Young," Hervey S. Stockman et al., Space Telescope Science Institute, Baltimore, MD, (pmomberg@stsci.edu), or http://oposite.stsci.edu/ngst/initial-study/

"When Galaxies Were Young," Anne Kinney, Astronomy Magazine, May 1998.

"Before the Beginning," Martin J. Rees, HarperCollins, 1998.

"The Inflationary Universe : The Quest for a New Theory of Cosmic Origins,", Alan H. Guth and Alan P. Lightman, Pegasus Press, 1998.

Figure Captions

Figure 1. COBE Science Team.

Figure 2. Spectrum of the 2.7 Kelvin cosmic microwave background radiation. Theory and observations differ by less than a part in 10,000.

Figure 3. Hot and cold spots in the cosmic microwave background radiation, showing the universe at an age of 300,000 years. Hot and cold spots differ from the average brightness by a part in 100,000.

Figure 4. One concept for the Next Generation Space Telescope, 8 m in diameter, to be launched around 2008 to see the first galaxies.