Accelerating the Cosmos

Cosmologists have discovered a new kind of energy that is speeding up the universe's expansion.

by James Glanz

There are times — very rare ones — when a journalist feels that he or she has been lucky enough to see the making of great science through a helmet cam. These miniature videocameras, mounted in the helmets of football running backs and baseball catchers, often reveal balls and bodies tumbling through the field of view, followed by huge grasping hands or approaching shoulder pads. The video image wobbles crazily before slamming to a stop against a piece of chewed-up turf.

I write about physics and astronomy for *Science* and my view of the discovery of the cosmological constant over the last two years has been as jarring as any athlete's in the heat of competition. The discovery, which astronomers made by observing the apparent brightness of distant, exploding stars called supernovae, has shaken astronomy to its core. Indeed, the discovery of the cosmological constant looks like one of the more important developments in any field of science in the 20th century.

Lawrence Berkeley National Laboratory's Saul Perlmutter and his colleagues used supernovae such as 1987A, background, to look for expansion much deeper in the universe.

Roy Kaltschmidt (Lawrence Berkeley National Laboratory) ments still farther: They have been tackling more distant supernovae and searching for any effect other than cosmic acceleration that could account for their findings. So far, they have found no reason to doubt their conclusions. Since the discovery is so unexpected, so important, and so heretical, the intense scrutiny will surely continue — exactly as it should in scientific research.

osmology Solved?

At the same time, particle physicists re studying the structure of space to etermine just what lambda might be. s source remains mysterious as new eas about its nature proliferate. Cosologists are perhaps the happiest oup of all with the sudden change. ne of them is Michael Turner of the niversity of Chicago. He refers to the smological constant as "funny energy." The amounts of it suggested by the new work could be just enough to square many different observations with inflation theory, the leading theory describing the first moment of the universe.

In fact, several years ago, before the supernova results even appeared, Turner and a handful of others had the audacity to suggest that a cosmological constant might someday be found. Last fall, Turner, in effect, exuberantly spiked the football and did a little touchdown dance during a talk in Washington, D.C., as he described how all known observations now fall into place with theory. The talk was entitled "Cosmology Solved? Quite Possibly!"

Einstein kicked off this astronomical contest in 1917. That was two years after he had formulated his theory of general relativity, showing how gravity bends space and moves matter around on large scales. Astronomers of the day thought the universe was static — neither expanding nor contracting. But when Einstein applied his relativity equations to the entire universe, he couldn't find a static solution. Failing to do so, he introduced the cosmological constant to prevent gravity from smooshing everything together and

Scientists with the Supernova Cosmology Project take images of tens of thousands of galaxies during new moon, when the night sky is dark. A few weeks later they observe the same regions of sky and electronically subtract pairs of images from one another. Brightening supernovae leap out when the two sets of images are compared. Cooperating telescopes that are part of a companion group, the Supernova Cosmology Project, follow the rise and fall of each supernova's "light curve." The peak brightness of each supernova, as seen from Earth, is a measure of its distance.

Supernova Cosmology Project, *Astronomy*: Terri Field making a big mess. He soon regretted his fudge factor, which he symbolized as lambda in the equations.

In 1929, the astronomer Edwin Hubble announced the results of a detailed study of the distances and recession velocities of galaxies with stars called Cepheid variables. The regularity with which these stars fluctuate tells their absolute brightness, and the "redshift" of the host galaxy — an apparent lengthening of the wavelength of their light, like the drop in pitch of a receding train whistle — gives a gauge of the speed at which they are moving away from us. Hubble found that the farther away a star's host galaxy, the faster its recession, indicating a uniformly expanding universe.

A Constant With Varying Appeal

Expanding universes were permitted in Einstein's equations, either with or without a lambda, so Einstein discarded lambda as an unnecessary complication. From that moment on, theorists occasionally found the cosmological constant useful, but it somehow felt slightly illicit, like using too many players on a team. Lambda's popularity eventually waned altogether. "If you have learned cosmology anytime in the last 25 years, you probably learned it without the cosmological constant as part of the course," Saul Perlmutter of Lawrence Berkeley National Laboratory, who heads the Supernova Cosmology Project, said in a recent lecture on his team's results.

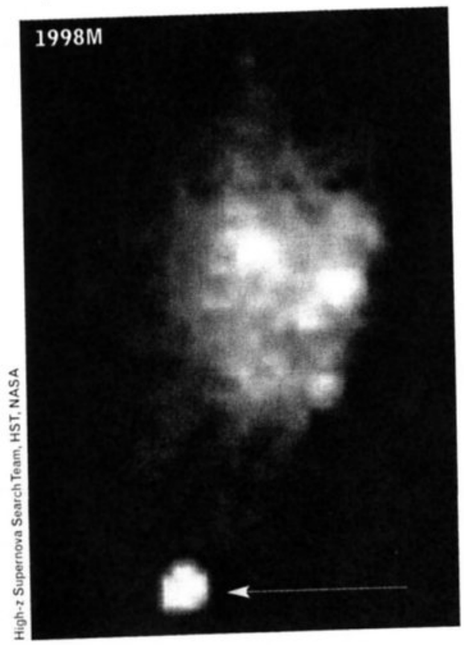
In the decades after Hubble's discovery, astronomers gradually realized that supernovae might let them look for expansion much deeper in the universe, beyond the realm of Cepheid measurements. Unfortunately, severe technical problems prevented astronomers from realizing that promise: Since type Ia supernovae go off only about twice per millennium in a typical spiral galaxy, how could astronomers ever observe enough of them to do cosmology? Surprisingly, the Cold War helped provide a solution.

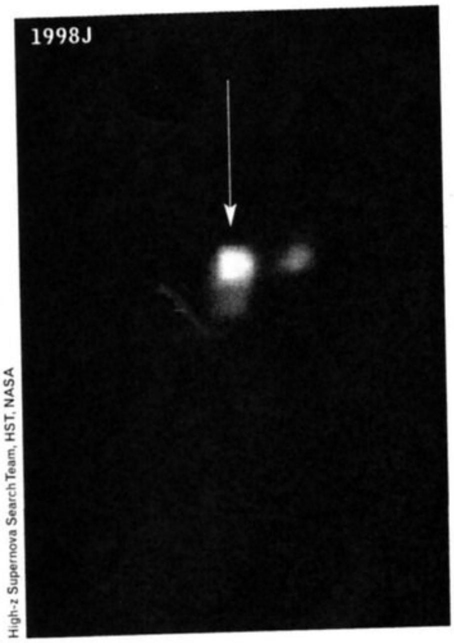
Stirling Colgate, the brilliant and famously uninhibited physicist at Los Alamos National Laboratory, provided the first glimmer of an answer. In a 1979 paper titled "Supernovae as a Standard Candle for Cosmology," Colgate's idea was that robotic telescopes would continually scan the nocturnal skies for the transient brightenings of supernovae. When one turned up, astronomers would be automatically notified so that they could do follow-up observations of the events. Colgate once explained to me that his original inspiration for the robotic supernova search had nothing to do with cosmology. He said that in 1959, he was part of a team negotiating with the Soviet Union on satellites that would monitor atmospheric nuclear blasts from space by detecting the gamma rays that emerged from them.

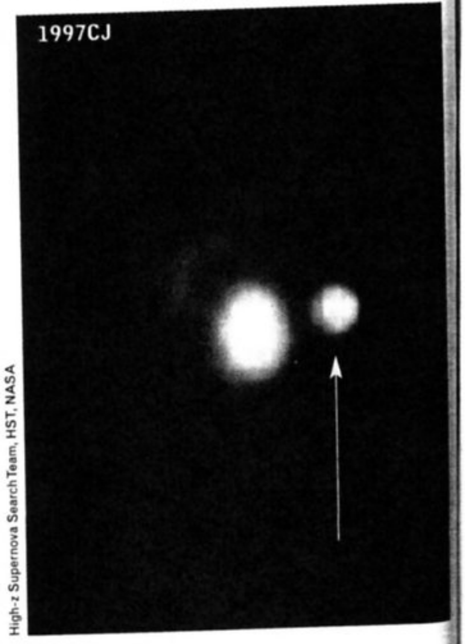
Eventually, the American Vela satellites were launched to detect the nuclear blasts, but Colgate said the Russians at first claimed that supernovae could cause false alarms. At the time, no one knew what a supernova would look like with such detectors. Colgate, the cold warrior, had an answer: "I said, 'You son of a bitch, I'll show you.'" Despite his laudable intentions, Colgate eventually realized that the computing power and electronic light detectors available at the time were not up to the robotic-telescope task.

Later a Danish group followed up on the general idea, flying back and forth between their home country and a telescope in South America. But after a period of many months, the Danish group had accumulated "a whole bunch of frequent-flyer miles and one supernova," says Robert Kirshner of the Harvard-Smithsonian Center for Astrophysics and a member of the High-z Team. One supernova is not enough to do cosmology. Little changed until one day in 1987, when Perlmutter and Carl Pennypacker, then both graduate students at UC Berkeley, sat around trying to come up with ideas for new research directions. They wanted to find something that would help them declare intellectual independence from their mentor, Rich Muller, himself a protégé of Nobelist Luis Alvarez. By then, computers were more powerful, and charged-coupled devices — or CCDs, the light-sensitive chips that function as "electronic film" — were becoming larger and more reliable all the time.

Perlmutter was actually operating a robotic telescope to seek out nearby supernovae and search for a dim star that Muller and others had postulated might be in a highly elongated orbit around our sun with a period of 26 million years. Muller and others thought that the star could potentially







disturb the Oort Cloud of comets that swarm around the solar system about 1 to 2 light-years from the sun. If that occurred, the star could cause some of the comets to rain down on the inner solar system and pummel Earth, resulting in an environmental catastrophe. Perlmutter never found the theorized death star. (He never disproved its existence, either: The project suffered from weak financial support.) However, the robotic telescope was able to identify 20 nearby supernovae.

Perlmutter and Pennypacker decided the time might be right to search for supernovae farther away — just as Colgate had envisioned. "Basically we took his idea and we updated it," says Perlmutter. "We called it the 'deep search.' The idea was to go out far enough that you could be relevant to the changes in the Hubble constant. That would be a deceleration parameter, as we thought."

In this case, the great distances actually worked in their favor since even a small swatch of sky would contain swarms of the host galaxies. Moreover, the universe's expected deceleration could be studied without knowing the exact value of the Hubble constant itself, just as you can sense that a car is slowing down without looking at the speedometer. Ultimately Perlmutter and a growing list of cosmological teammates came up with a plan to observe tens of thousands of galaxies during new moon, when the night sky is dark. A few weeks after those observations, the same regions of sky would be observed and the two sets of images "subtracted" electronically on computers. A brightening supernova would leap out, allowing other telescopes to follow the rise and fall of its "light curve" and determine the peak brightness as seen from Earth.

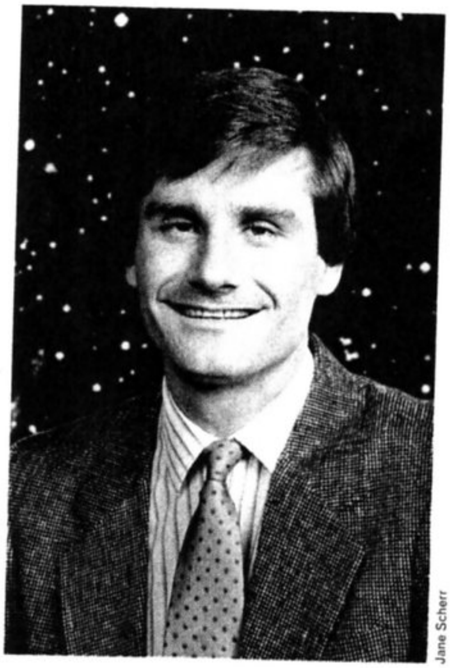
Astronomical Culture Clash

Effective as this supernova search turned out to be, this wholesale method was seen as a thumb in the eye of the prevailing astronomy culture. Astronomers compete for time on top-notch telescopes and regard it as something precious, planning intensive observations of one or two objects of interest and learning everything possible about them. Perlmutter was talking about catching 40 or 50 supernovae and throwing the bad ones away. Such an approach was routine for particle physicists in the Alvarez group, but almost unthinkable for most other traditional astronomers.

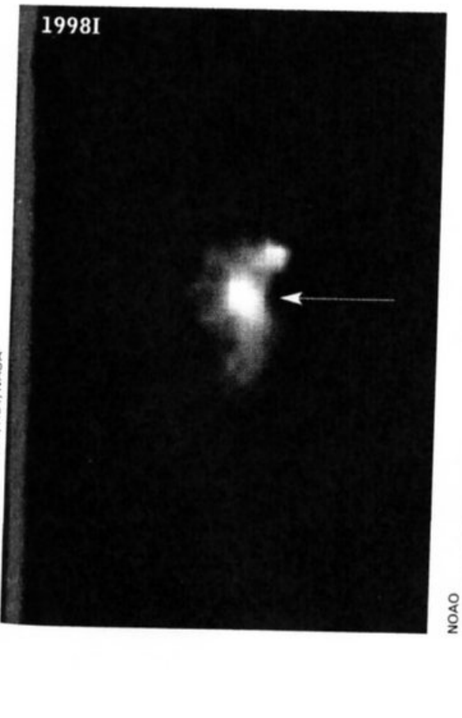
To make matters worse, the secretive and powerful scheduling committees on major telescopes were prepared to grant him random slots of free time; however, they didn't respect the rhythm needed for his research algorithm. "They had a long tradition of never telling anyone anything until it was all a fait accompli, until there was already a schedule written," said Perlmutter. "And at that point, they would never touch it, because they would be taking away someone's time and that person would really be angry. So we had to work our way into that sociology."

Perlmutter became friends with the schedulers of about half the major telescopes around the world. By 1994, the observations were in full swing. Meanwhile, the High-z Team formed and chose Brian Schmidt of the Mount Stromlo and Siding Spring Observatory in Australia as its leader. Schmidt had done his Ph.D. under Kirshner. Not coincidentally, developments elsewhere were making type Ia supernovae look like even better distance indicators. Mark Phillips of the Cerro Tololo Inter-American Observatory in Chile had completed a careful study of nearby type Ia supernovae and found that a slower rise and fall in the light curves indicated higher peak brightness, allowing for an even better read on the wattage of these brilliant "light bulbs."

Why the brightness correlates to the rise and fall of a supernova's light output is not precisely understood. The explosions are thought to originate from a particular type of white-dwarf star — a dim, dense, stellar cinder made mostly of carbon and oxygen. Its strong gravity may gradually suck material from a companion star. Eventually, the growing white dwarf passes a threshold called the Chandrasekhar limit and begins to collapse under its own weight. In the collapse, the core heats rapidly, igniting a colossal thermonuclear explosion.


Jane Scherr

Alexei Filippenko of UC Berkeley and the High-z Team calls type Ia supernovae "these wonderful bombs that nature has given us."



High-z Supernova Search Team, HST, NASA

NOAO

These are some of the type Ia supernovae that have helped astronomers calculate that the expansion of the universe is accelerating.

Jon Chase

High-z Team member Robert Kirschner notes that astronomers involved in prior supernova searches had scant luck.

Oddball Datum

Perlmutter's Supernova Cosmology Project actually found a few supernovae and the excitement soared. But there remained a few drastic reversals before the cosmological constant lit up the scientific scoreboard.

By the summer of 1995, Perlmutter's group had mostly completed the analysis for one distant supernova and had partially analyzed six more. (The light curves take weeks or months to rise and fall, and it can be a year before the astronomers obtain a final image of the host galaxy without a trace of supernova light, a necessary step in calibrating all the many previous telescope observations.)

One of those first supernovae, however, turned out later to be an "outlyer," a statistical oddball. "Their preliminary analysis of one supernova already casts doubt on a strongly accelerating expansion — the mark of a cosmological constant in a low-density universe," I wrote in *Science*. Almost exactly a year later, with those conclusions still regarded as preliminary, I was writing about a series of debates on the campus of Princeton University dealing with cosmological questions. In one Princeton debate, Turner, the Chicago theorist, was arguing for a position that then seemed unlikely, to put it mildly: He maintained that theoretical and observational evidence suggests that the universe has a low density of matter, which would favor the expansion of the universe. He also argued that the cosmological constant supplements the expansion. Turner conceded that if Perlmutter's early conclusions held up, this heretical view could not possibly be right. But in the most striking example of a theorist's hubris (and, as it turned out, foresight) I have ever witnessed, Turner warned Perlmutter that because the supernova results were still not definitive, they should not be presented during the Princeton debates.

At one point, a chattering crowd of astronomers and cosmologists were climbing a flight of stairs to an auditorium after a break in the action. Turner was a few steps below Perlmutter. I walked on one side of Turner, and on the other side walked astronomer Wendy Freedman of the Observatories of the Carnegie Institution of Washington. As if he were feigning to speak to Freedman, Turner raised his voice slightly in commenting on Perlmutter's plan to announce his preliminary results (I alter the language slightly for reasons of politeness): "I don't think Saul is that unenlightened." Perlmutter did not seem to hear. Turner then shouted: "I said I don't think SAUL is that UNENLIGHTENED."

Just to make sure no one missed the point, Turner gave another version of this admonition during his own talk. "I am anxiously awaiting the results of the two deep searches for supernovae," he said. "I think they're going to shed some important light on this. To draw any conclusion now would be to take away from their thunder later." For whatever reasons, Perlmutter didn't give his planned talk. The Supernova Cosmology Project did publish its results — and properly so, since the astronomical community deserved a chance to examine and comment on them. Nevertheless, the real thunder was coming.

The first observations were made from the ground, through the distorting confusion of Earth's atmosphere. By late the following year, not only had both groups refined their observing strategy from the ground — they had also made the leap into orbit. They won observing time on the Hubble Space Telescope. Acting on a tip, I wrote a story, published October 31, describing the first sketchy evidence from both groups that cosmic expansion did not seem to be decelerating at all. The cosmological constant was mentioned as a possible culprit, but that reasoning still seemed too strange to take seriously. In any event, the conclusions were still based on a mere handful of supernovae.

Fateful Conversation

The game changed radically at an American Astronomical Society meeting in Washington, D.C., in January 1998. The two groups scheduled a joint press conference in which — according to the press releases given out beforehand — they would formally present the results I wrote about the previous October. I skipped the press conference, thinking I had better things to do, but fortunately ran into Perlmutter later that day. We sat down at a table in the commons area of the conference. After a few minutes of conversation, he told me that he had presented new observations at the press conference: 42 supernovae. The data had not been fully analyzed yet. But there was some suggestion, he said, that there could be "a huge cosmological constant."

Bells started going off in my mind. I asked him to explain. On average, he said, the supernovae were dimmer than expected, implying that cosmic expansion has sped up. Perlmutter cautioned that the group was still correcting for possible dimming of the light by dust and that the conclusions could still change. But I folded my steno pad and hurried away in pursuit of another conference participant — the talkative Chicagoan, Turner.

"It would be a magical discovery," said Turner. "What it means is that there is some form of energy we don't understand" — the cosmological constant that he had defended in the Princeton debates. My report in *Science* came out on January 30. Out of the huge press contingent at the meeting, a few other publications — including the *San Francisco Chronicle*, *U.S. News & World Report* and *Astronomy* — also picked up on the importance of what Perlmutter was saying and reported it, usually in low-key fashion.

Things didn't really break loose until a month later when the High-z Team was about to announce the confirmation of the Perlmutter results at a small conference in Marina del Rey, California. The High-z Team had actually completed their dust corrections

High-z Supernova Search Team, HST, NASA

ɪ the suggestion of a cosmological ıstant was, if anything, even stronger their data. Working quietly, I interwed cosmologists both inside and side the team and wrote one of my st important stories. This time all of major daily newspapers, news magıes, and electronic media picked up story.

Soon, an unusual, but understande, note arrived. It was from Brian midt, the High-z Supernova Search m leader: "My own reaction is ıewhere between amazement and ror. Amazement, because I just did expect this result, and horror in wing that it will likely be disbeed by a majority of astronomers —), like myself, are extremely skepti- of the unexpected." His fear was ially borne out. During a lecture at White House a short time later, phen Hawking, the University of nbridge cosmologist, was asked ut the new supernova results and uggested that they were too prelimy to be taken very seriously. But throughout the rest of the year the results became stronger as fresh data came in and no one could find a flaw in the teams' analysis.

rnova 1994D, lower left, which exploded e outskirts of galaxy NGC 4526, is one ›re than 120 type Ia supernovae discovin the past few years.

Breakthrough Story

In December 1998, *Science* named the accelerating universe the "Breakthrough of the Year." In March 1999, during a press conference at a meeting of the American Physical Society in Atlanta, I asked Hawking whether he had changed his mind. "I have now had more time to consider the observations, and they look quite good," Hawking said with his synthesized voice. "This led me to reconsider my theoretical prejudices. I now think it is very reasonable that there should be a cosmological constant."

Later, as I walked up to thank Hawking for fielding questions, Gerson Goldhaber appeared, looking distinctly pleased. He was one of the first members of the Supernova Cosmology Project to argue that the data supported a cosmological constant. He had been standing in the back of the room. He also wanted to thank Hawking. "I wouldn't say I think the evidence for a cosmological constant was cast iron, but it is as good as many things in cosmology," Hawking added. Not wishing to lose the quote, I reached for my steno pad, opened it and began scribbling while repeating the words as I remembered them, unsure whether I had it exactly right. Hawking kindly hit a button and replayed his comment on his synthesizer. I thanked him again.

The two groups have been busy since then. The Supernova Cosmology Project will soon have completed the analysis of 80 supernovae, while the High-z Team has analyzed about 40.

Both groups are currently in the midst of observing runs, with dozens more supernova discoveries expected. Ever more detailed examinations of both nearby and distant supernovae are under way to try to find any hint that they fall short as standard candles — a search that has so far been agreeably unsuccessful. Perlmutter has even proposed a dedicated satellite that would observe thousands of supernovae from space using new CCD technology developed at Lawrence Berkeley National Laboratory.

These days, I feel a bit drained by the cosmological constant story, as if I had lived through five Super Bowls — all with close scores — and a World Series or two. Although the observational case continues to strengthen, the importance of the discovery ensures that it will continue to be challenged at every turn — as it should be.

What physical entity is responsible for the constant? Nobody knows. The so-called "funny energy" could be anything from the evanescent particles that quantum mechanics says should pop in and out of existence to a weird, fluid-like substance called quintessence, a squishy possibility that might be pinned down with the vastly increased numbers of supernovae possible with the satellite.

Oddly enough, now that particle theorists have started thinking about this new funny stuff, their calculations are producing too much of it rather than too little. Of course, theorists are like that.

Once it's all been settled, I'm going to crack open a beer, kick back, and count myself lucky to have reported some of the century's most thrilling scientific action. ■

James Glanz covers physics and astronomy for Science.