The idea that the universe as we know it was born in a split second of exponential growth is cosmological gospel. But no one can agree on a single version of the theory called inflation

Which Way to the Big Bang?

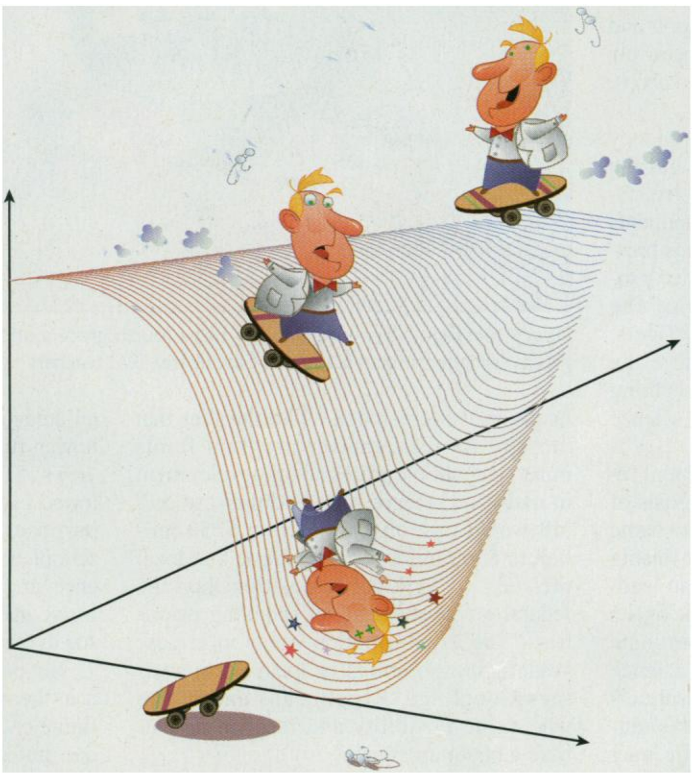
CHICAGO—Every story has a beginning, and according to standard cosmology, the story of our universe began with a bang. In this story, an epic that resonates through decades of scientific studies, all the stars, galaxies, planets, and shadowy gases of the heavens can be explained if the universe consisted of a superhot, superdense, outrushing ball of matter and light just a fraction of a second after the moment of creation itself. That very tale, however, begs the question of what happened in the mysterious instant just before the conflagration began, some 13 billion years ago. If there was a big bang, what set it off?

In the years since Alan Guth wrote the words SPECTACULAR REALIZATION in his notebook in December 1979, cosmologists have come to think that the big bang might be explained by an idea they regard as a thing of beauty. Called inflation, the mechanism Guth proposed for igniting cosmic expansion in all its glory might have operated for as little as 10^{-35} seconds. Yet it could have whipped up all the matter and energy in the universe and laid the seeds for galaxies and galaxy clusters in that brief sliver of time, while the universe blossomed exponentially from as small as 10^{-24} centimeters across to perhaps the size of a pumpkin. Ever since then the universe, expanding at a more leisurely pace, has been living off the legacy of this episode. "Inflation," says Michael Turner of the University of Chicago, "is the most important idea in cosmology since that of the big bang itself."

The theory relies on the notion that the vacuum of space is not empty. According to particle physics, space can be suffused with the energy of so-called scalar fields, which control the symmetries and asymmetries of material properties, such as particle masses, and can dissolve into a storm of particles when disturbed. A special kind of scalar field, which owes its existence to a mysterious particle called the inflaton (pronounced IN-flah-tahn), would have sparked the big bang. If just "once in all of eternity," says Guth, who is at the Massachusetts Institute of Technology, the inflaton in a tiny patch of space found itself in an unusual, energetic state—analogous to a ball pushed far up a hill—the patch would have behaved as if gravity were thrown crazily into reverse, expanding exponentially.

The concept of inflation is so venerated that Guth's notebook page, carefully dated "Dec 7, 1979," sits behind glass in a gallery beneath the Adler Planetarium here. And so far, the idea meshes with the broad outlines of what astronomers have learned about the cosmos. Even so, there is no proof that inflation is correct; and, to add to the uncertainty, distinct versions of the theory have proliferated, as physicists grapple with the problem of finding an inflaton that could have produced the universe but is also compatible with known laws of physics. For some cosmologists, that cacophony means that the choiring angels of creation have not been heard quite yet. As Lawrence Krauss of Case Western Reserve University in Cleveland puts it, "Inflation is a beautiful idea in search of a model."

Or, rather, a single believable model. The theory now comes in varieties called old, new, chaotic, hybrid, and open inflation, with numerous subdivisions like supersymmetric, supernatural, and hyperextended inflation, each a vision of just how the inflaton might have touched off the birth of the universe we see today. In fact, there now exist so many approaches, with such a wide range of predictions, that a few cosmologists have suggested inflation could never be disproved by observation—a prospect Andrew Liddle of Imperial College in London calls "a bit scary."



Hybrid inflation. A recent version of the theory posits a 3D energy landscape. The universe inflated as it moved down a gently sloping energy ridge; then it plummeted from the ridge, shutting off inflation and igniting the big bang.

Such concerns have prompted the search for alternative theories of creation, whose predictions could be compared mano a mano with those of inflation (see sidebar, p. 1450). But other cosmologists think an avalanche of new data on the cosmic microwave background radiation (CMBR)—a sort of afterglow of the big bang—is about to put the inflationary framework to its toughest test yet. Each model has distinctive predictions about the ripples of higher and lower density that inflation would have imprinted on the young cosmos. Those ripples should still be visible in the CMBR, and new instruments that will fly aboard balloons and satellites over the next few years will measure them. The new measurements "will consign to the rubbish bin of history most of the proposed models of inflation," predict David Lyth of Lancaster University in the United Kingdom and Antonio Riotto at CERN in Geneva in a forthcoming review article.

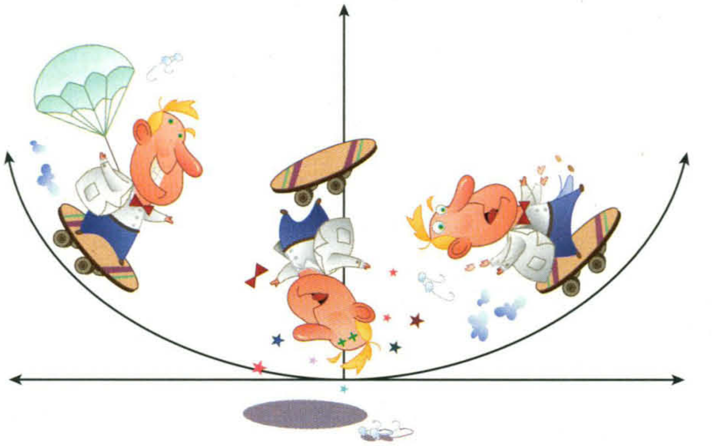
Some cosmologists are looking back even further, to ask what set the stage for inflation itself. No one knows whether that

ILLUSTRATIONS: TERRY E. SMITH

question even makes sense, although in some theories the beginning can be calculated and might even have subtle observational consequences in the CMBR. "It's written up there in the sky," says Chicago's Rocky Kolb, "and we have to figure out how to read it."

Genesis of an idea

Alexei Starobinsky at the L. D. Landau Institute of Theoretical Physics in Moscow worked out a somewhat complicated version of inflation in 1979. But it was Guth's version in the same year that jolted the scientific community, because he pointed out that it might solve several cosmological puzzles. For one thing, the universe is remarkably "flat"—light travels great distances through space without revealing any curvature—implying that it contains a certain critical density of matter and energy. That flatness had looked uncomfortably like a lucky coincidence; inflation made it into a natural consequence of early cosmic history.



Chaotic inflation. In this version of the idea, cosmic expansion generates a drag (parachute) that slows the universe's plunge from the heights of an energy landscape, prolonging inflation.

Guth's original idea, now called old inflation, invoked the concept of phase transitions, like water changing into ice. The phase transitions Guth was interested in, however, involved the forces of nature. Three of them—the strong, weak, and electromagnetic forces—should merge into just one at extremely high temperatures, according to certain untested theories of particle physics, called grand unified theories (GUTs).

Those temperatures, corresponding to energies of 10^{16} billion electron volts, could never be reached in terrestrial particle accelerators. But an infinitesimal mote of spacetime at the very start of the big bang could provide them. That superhot mote (however it came about) could have cooled like a spark in the wind, but Guth further supposed that the high-temperature symmetries persisted for a brief instant after the temperature had dropped below the GUT scale.

Such "supercooling" is familiar from ordinary phase transitions. Water, for example, can remain liquid even though it is cooled below 0° Celsius—until it suddenly freezes, losing its amorphousness and taking on the jagged asymmetries of crystalline ice. According to particle physics, supercooling would leave space itself hovering in a state of unnaturally high energy, a condition called a "false vacuum." This energy can be thought of as residing in a scalar field filling that speck of space. When Guth plugged the false vacuum into Einstein's equations of relativity, he found that it acted like gravity in reverse.

"I discovered that it would affect the expansion in a tremendous way," says Guth. "It would cause a gravitational repulsive effect that would drive the universe into a period of exponential expansion." Once the asymmetries finally froze in and the forces took on separate identities, the vacuum would plunk into its "true" state, liberating the energy as an exploding ball of particles and radiation, like the latent heat given off when a supercooled liquid freezes. Even better, the exponential stretching would create a geometrically "flat" space.

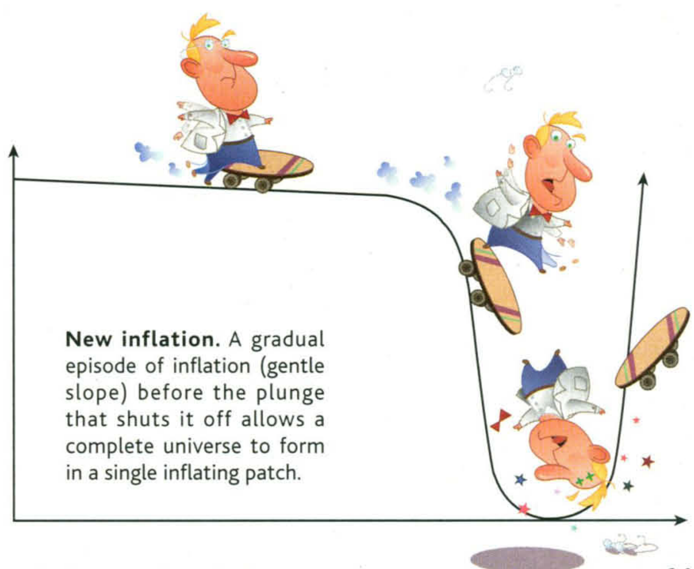
Incredibly, creation seemed to be calculable. But there was a problem with old inflation, as Guth and Erick Weinberg of Columbia University realized immediately. Bubbles of true vacuum would form at various times in various places in the false vacuum and would have great difficulty merging, because the space between them would still be inflating. "You'd always end up with a cold, Swiss cheese–like universe," says Paul Steinhardt of Princeton University, "with true vacuum contained only in growing bubbles … and nothing there that looked like the universe in which we live."

That mix of ethereal success and final disaster made Guth's talks both exciting and "profoundly depressing," Steinhardt recalls. Much of the depression lifted when he and Andreas Albrecht of the University of California, Davis, and independently, Andrei Linde, now at Stanford University, invented new inflation. The idea was to make the transition from false to true vacuum very gradually, so that instead of the quick jump—which left plenty of false vacuum but not much of the ordinary space in which we live—an entire universe would have time to grow inside each bubble and there would be no need for many of them to merge. (Separate bubbles would still be separated by huge tracts of false vacuum and hence unobservable to each other.)

The change in the scalar field's energy at each point in the false vacuum of supercooling can be envisioned as a ball rolling down a hill; old inflation was equivalent to a hill with a dimple at the top, where the supercooled universe would get stuck before suddenly tunneling, via quantum-mechanical processes, down to the true vacuum. New inflation simply posited a hill with a nearly flat top, where the ball would slowly roll out of the false vacuum as the universe inflated, followed by a drop-off as it suddenly crystallized into true vacuum.

By eliminating the bubbles from Guth's original scenario, this new version allowed inflation to explain a second cosmological puzzle: the remarkable uniformity of today's universe. By stretching a tiny region into the entire universe, inflation could explain how regions so far apart that they could have had no communication since the big bang could appear so similar.

But turning this beautiful idea into a full-fledged theory was proving difficult. Although the shape of the hill, called the



New inflation. A gradual episode of inflation (gentle slope) before the plunge that shuts it off allows a complete universe to form in a single inflating patch.

Wanted: New Creation Stories

CHICAGO—"I am going to speak of a very radical idea," said Andreas Albrecht, a cosmologist at the University of California, Davis, during a recent symposium here. Albrecht's modest proposal was a way to produce a universe that looks like the one we inhabit but never underwent a growth spurt at the beginning of its history. Most cosmologists think the remarkable homogeneity and geometric flatness of the large-scale universe is the result of inflation, which would have stretched a tiny mote of space and time into the entire cosmos (see main text). Albrecht's alternative suggestion is that cosmic smoothness and flatness might be the product of a speed of light, *c*, that was much faster immediately after the big bang.

Even Albrecht concedes that speeding up light—whose constancy forms the bedrock of Einstein's theory of relativity—is a tall order. But he is one of a tiny number of researchers—another being Gabriele Veneziano of CERN, the European particle physics lab in Geneva—who feel it's important to give inflation some competition, so that it doesn't become the reigning theory of the big bang by default.

Albrecht's approach, which he is working on with Joao Magueijo of Imperial College, London, simply assumes that *c* was tremendously larger at some time during the universe's first fraction of a second. In principle, that would allow distantly separated regions to exchange energy and come to the same temperature in a universe that is assumed to be expanding already. The mechanism would be particularly effective at creating a flat and homogeneous universe, because the equations that show how matter responds to a changing *c* also create and destroy energy, relentlessly dumping it into thermal dips while taking it away from peaks.

"You actually produce a universe that is very, very smooth," says Albrecht—too smooth, in fact, for matter ever to have coagulated into galaxies and clusters of galaxies. Albrecht has to invoke some other mechanism for producing the seeds of structure—for example, so-called "defects," hypothetical seams in space-time.

Veneziano wouldn't eliminate the growth spurt but would give it a radically different driving force. His scenario is based on string theory, a mathematical framework many physicists hope will provide a unified picture of all the forces of nature, including gravity. In his "pre–big bang" scenario, there's no need to invoke inflation theory's energy-rich "false vacuum" to kick off the exponential expansion. Instead, the gravitational collapse of a collection of matter or gravity waves in some preexisting universe gives birth to a new, expanding universe like our own. "In this picture it becomes not a crunch but a bang," says Veneziano.

In Veneziano's scenario, our universe and a collapsing precursor are connected by a string "duality," a mathematical correspondence between two very different theories that can be linked via a simple change of variables. The duality invoked by Veneziano connects a collapsing universe with ordinary gravity into an expanding one with powerfully repulsive gravity. What flips the switch for the duality to take effect still isn't clear, but there is no question about the main observational signature of the theory: a universe awash in gravity waves, which might be measured by the gravity wave detectors now being built for other purposes.

Don't bet on it, though. Most researchers don't think the alternatives are much of a threat to inflation yet. And Albrecht himself admits that the effort to come up with an alternative has mainly left him "impressed with what a powerful idea inflation is." –J.G.

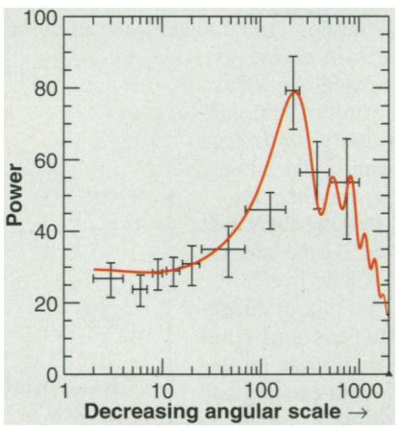
potential-energy curve, should ultimately be derived from particle physics theory, that was easier said than done. In the end, cosmologists decided not to worry for the time being about the physics that drove inflation. They simply attributed the potential energy curve to a still-to-be-discovered particle, the inflaton. As Albrecht put it, inventing the inflaton was a way of saying, "Look, what's the point of putting in the whole baggage of the GUT when we really don't have a clue of physics at those energy scales?"

After all, the idea was getting a boost from observation. Inflation should have left ripples of higher and lower density on the early universe, because quantum uncertainty means that the ball would roll at slightly different rates in different places. The ripples could serve as the seeds around which gravity eventually gathers the colossal walls, filaments, and clusters of galaxies seen in the sky today. And in 1992, the Cosmic Background Explorer (COBE) satellite mapped the CMBR—which records the state of the universe 300,000 years after the big bang—and detected huge, weak ripples crisscrossing the early universe.

Just as expected if the ripples in the universe really did start out as quantum fluctuations in the microworld, the COBE observations suggested that the intensity, or "power," in the ripples was nearly the same at all wavelengths. "Inflation played this trick," says Linde. "It took something that was very, very quantum and enormously stretched it and made large, macroscopic objects."

Many kinds of beginning

With this boost, inflation theorists began enthusiastically spinning out their own versions of creation. Linde, for example, showed that a plateau-shaped potential was not necessary after all; a simple parabolic slope or many others would do, as long as they were wide and shallow enough to let the ball start at a high energy—at the GUT scale or beyond. The ball still drops slowly because of a frictionlike term that can be traced to the rate of cosmic expansion. "It's, if you want, God's gift to us," says Linde of the friction term. He named the theory chaotic inflation, imagining a primordially random cosmos in which patches that happened to be high on the potential would inflate, while others would not. Just one favorable beginning could lead to a universe.



Glimpse of mountains. The peaks in a predicted power spectrum of the microwave background, showing angles where fluctuations are strongest, are an expected signature of inflation. Early data (crosses) seem to fit predictions.

Eventually it turned out that inflation didn't have to make a flat universe; it could also create "open" universes—those with a spatial curvature corresponding to the low cosmic matter densities that some observations were pointing to. Although regarded by many cosmologists as less than elegant, the theories contrive to have the universe fall from the heights of the inflaton potential, ending the inflationary epoch, before space has been completely flattened.

The floodgates opened even wider with what came to be called hybrid inflation. Those models allowed two coupled inflaton fields to form a sort of three-dimensional landscape, so that the ball could roll slowly along a ridge, but then shut inflation off by plummeting sideways (see figure, p. 1448).

CREDIT: MICHAEL TURNER

Some cosmologists say hybrid inflation gives them more freedom to reestablish contact with particle theories—especially supersymmetry, a speculative theory that predicts the existence of new particles. The idea, says Princeton University's Lisa Randall, is to find "natural" fields—"not some artificially designed potential that has whatever features you want."

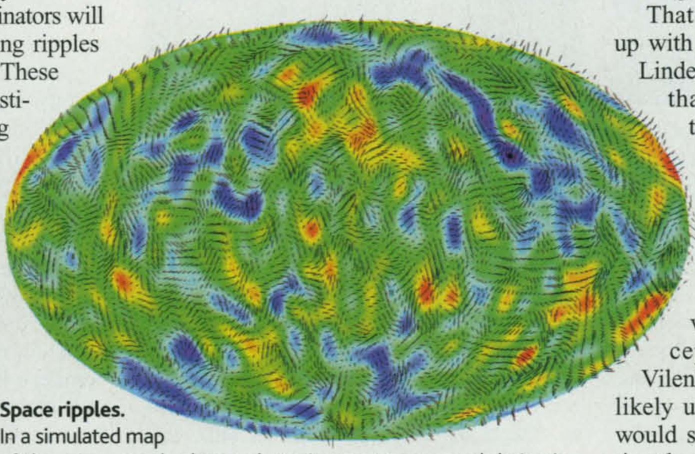
For all the inventiveness of inflationary modelers over the past 2 decades, says Turner of the University of Chicago, no version stands out as more compelling than the rest. "It's like 4-day-old babies in the maternity ward," he says. "Most of the theories are only attractive to the person who proposed them." Fortunately, improving observations should supersede the theoretical beauty contest. Among the most powerful discriminators will be follow-ons to COBE, measuring ripples in the CMBR to high precision. These projects include the California Institute of Technology–led Boomerang experiment, which flew a balloon-borne detector around Antarctica in December, yielding data that are now being analyzed; NASA's Microwave Anisotropy Probe (MAP) satellite, scheduled for launch late next year; and the European Space Agency's Planck satellite, now planned for 2007.

Such measurements should provide a test of one prediction that most variants of inflation still make, namely, that the universe is geometrically flat. In the first years after the big bang, oscillations would have resonated through the expanding ball of ionized gas as gravity tried to compress some regions, generating acoustic waves. "It's quite like a musical instrument," explains Wayne Hu, a cosmologist at the Institute for Advanced Study in Princeton, New Jersey. "You see one fundamental frequency and then overtones." After 300,000 years, the universe cooled enough to let free electrons combine with nuclei, making the gas transparent and releasing the radiation we now see as the CMBR.

The radiation emitted then should contain an imprint of the density peaks and valleys of the resonances. The wavelength of the main resonance—called the first Doppler peak of the CMBR—represents the distance sound waves could travel in 300,000 years. And because the speed of sound and the distance the CMBR traveled to us are both roughly known, the wavelength of the first peak is essentially a measuring stick laid out of the sky at a known distance. From its apparent size as seen from Earth, cosmologists can calculate the properties of the lens through which we are viewing it—the geometry of space.

If space is flat, the peak should have an apparent scale of about 1 degree on the sky—twice the width of the full moon. COBE could not map the CMBR in fine enough detail to see this peak or the smaller harmonic peaks. But data from more recent mapping efforts are already suggesting a peak at about 1 degree (see graph on opposite page).

The kind of perturbations that COBE saw, which were created by quantum fluctuations during inflation itself, should provide more stringent tests. Inflation predicts that the intensity of the quantum fluctuations should have been nearly the same at all scales—but not exactly. If the cosmic ball was speeding up or slowing down at the end of the slow-roll epoch of inflation, the fluctuations should depart just a bit from "scale invariance." Planck or MAP might measure the deviations, which would say something about the shape of the inflaton potential—and therefore about which inflation models might be right.



Space ripples. In a simulated map of the microwave background, gravity waves generated during inflation sculpt the microwaves' polarization (bars).

CREDIT: R. CALDWELL, M. KAMIONKOWSKI, L. WADLEY

Other cosmologists, such as Marc Kamionkowski of Columbia University, are focusing on another kind of signature inflation could have left in the CMBR. Quantum processes during inflation could have left ripples in the curvature of space itself—gravity waves, which might still be crisscrossing the universe. Much as ripples on the surface of a swimming pool seem to distort the bottom, these waves would leave their mark on the polarization of the microwaves. "If you detect the gravitational background, it would be a smoking gun signature of inflation," says Kamionkowski.

Begin the begin

The possibility that observations could vouchsafe a glimpse of the universe's first 10^{-35} second has cosmologists pondering the ultimate question of how and why inflation might have started. To paraphrase a line from the folk tune *Alice's Restaurant*, "What put that ball at the top of that hill?"

According to one line of reasoning based on separate work by Alex Vilenkin of Tufts University and Linde, the ultimate beginning could be forever hidden from our view. They noted that virtually any type of inflation is "eternal": The initial patch of false vacuum will make not one inflating universe but will break up and generate infinitely many. As bubble universes are generated ad infinitum, the false vacuum becomes so stretched and smoothed that no trace of its beginning remains. For practical purposes, says Vilenkin, "you would not have to think of the beginning of the universe."

That hasn't stopped him from coming up with a vision of the beginning. He and Linde have tried to calculate the chances that the first inflating patch could tunnel into existence, quantum-mechanically, from absolute nothingness. They took the point of view, as St. Augustine did in his *Confessions*, that neither time nor space could have existed before the instant of creation. Assuming various inflaton potentials—a concept outside Augustine's canon—Vilenkin and Linde found that the most likely universes to burrow into existence would start out high on the potential, setting the scene for a cosmos like our own.

According to another trio of cosmologists, however, questions about the moment of creation have no meaning. The mathematical formalism developed by Stephen Hawking and Neil Turok of Cambridge University and James Hartle of the University of California, Santa Barbara, makes it impossible to extrapolate the universe back to a singularity—a discrete starting point for time. "It's not creation from nothing," says Turok, "which I think is a complete contradiction."

Most of the universes that emerge from their scheme contain too little matter and are much too open to be in accord with current data. Turok is searching for new inflatons that might do better, but meanwhile he nurtures a hope that the universe will turn out to be open, even if only slightly, for that would mean that all traces of the beginning had not been completely stretched away to flatness and overlaid with the later quantum fluctuations. Although perfect flatness would be a victory for mainline inflation, Turok says, it "would just say that what came before doesn't matter. It would, in a way, end the story."

The answer to how far that story can be traced back will be discovered—as Augustine said, for his own reasons—in the testimony of the heavens.

—JAMES GLANZ