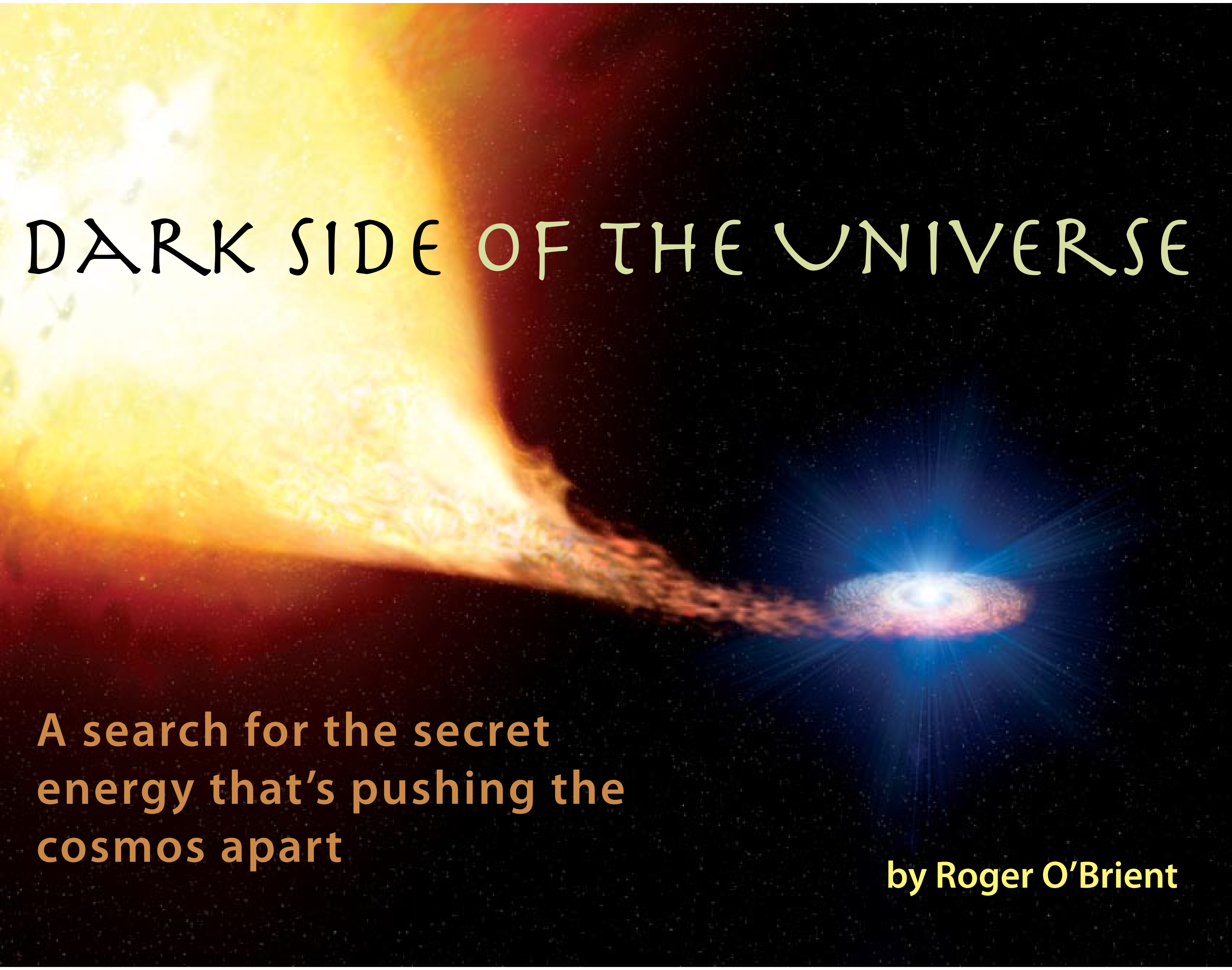


DARK SIDE OF THE UNIVERSE

A search for the secret energy that's pushing the cosmos apart

by Roger O'Brient

Artist's rendition of a Type Ia supernova.

GRAVITY IS A RELENTLESS FORCE. Twenty-four hours a day, seven days a week, it keeps our feet firmly planted on the ground, sending back down to Earth everything that goes up. Or almost everything. But even in those rare moments when man manages to escape the clutches of Earth's gravity with a rocket, it doesn't relinquish its hold easily—it pulls and tries to slow the craft all the while.

And so it is with the universe, physicists used to think. Since the Big Bang, galaxies have been hurtling away from one another. But just as with a rocket or a ball, gravity should act to slow the expansion down. Maybe gravity is strong enough to pull all the galaxies back together in a Big Crunch, like a ball that eventually returns to the ground from which it was thrown. Or maybe, like the rocket, the galaxies would continue to go forever, all the while slowing but moving just fast enough to keep going. Certainly, though, gravity would slow the expansion down.

In 1998, however, Berkeley physicist Saul Perlmutter made an astonishing discovery: our universe is actually expanding at an accelerating rate. This discovery, named 'scientific breakthrough of the year' by the journal *Science*, contradicted conventional cosmological theory and gave birth to the mysterious concept of "dark energy." Faced with the reality of an accelerating universe, physicists have been forced to reevaluate their assumptions about matter and energy. Einstein's theory of general relativity suggests that the universe must contain far more energy than science has thus far been able to measure. This energy is called "dark" because we can't detect it directly, just as "dark matter" was termed dark (though dark matter and energy are unrelated in every respect but name). The nature of this energy remains one of the key open questions in modern physics. Perlmutter and his colleagues at LBL, along with cosmologists around the world, are now in a race to provide a convincing answer to these open questions.

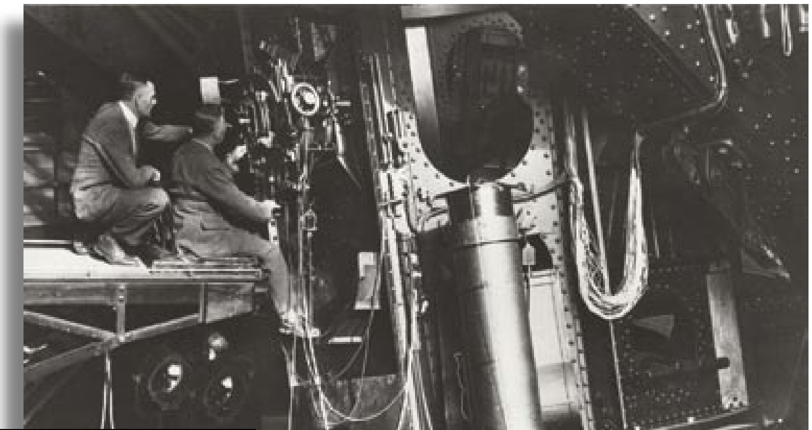
IMAGE COURTESY: NASA

Einstein's greatest blunder?

By 1917, Einstein had cooked up a stunningly beautiful theory that explains how gravity works: both energy and massive bodies like the Sun warp the fabric of space and time itself. In turn, other objects, like an orbiting planet, travel along the curved contours of this distorted space. While Einstein's theory of general relativity succeeded where Newton's theory of gravity failed, it made an unexpected prediction: the universe is either expanding or contracting. Convinced that the size of the universe must actually be static, Einstein corrected his equations by giving space-time itself an intrinsic repulsion that he called the "cosmological constant."

Experimental refutation of Einstein's static universe soon came from astronomer Edwin Hubble. High in the mountains above Los Angeles, Hubble first discovered that there are many galaxies beyond our own Milky Way. He also noticed an odd phenomenon: the light from these distant galaxies was shifted in wavelength toward the red end of the electromagnetic spectrum. He attributed this to the Doppler effect—the same process that causes the pitch of a siren to drop as it passes an observer. This implied that the galaxies were all moving away from us. Furthermore, if he made a graph of the speed of a star versus its distance from the Earth, the data points fell on a straight line. Such a plot has become known as a Hubble plot, and the slope of the Hubble constant, which quantifies the actual speed at which the universe is expanding. While these discoveries catapulted Hubble to the status of a legend among scientists and socialites*, Einstein was left feeling that the cosmological constant, resulting from his insistence on a static universe, was the "greatest blunder" of his life.

At first glance, Hubble's result poses a pretty serious problem: if everything is flying away from us, the Earth must



(Above) Edwin Hubble (on left) used the Hooker Telescope at Mt. Wilson Observatory in Pasadena, CA to take the first measurements of the universe's expansion rate in the 1920s. (Left) Supernova 1994D is one of many type Ia supernovae photographed by the Hubble Space Telescope.

HUBBLE PHOTO COURTESY: CARNEGIE INSTITUTION.
SUPERNOVA IMAGE COURTESY: NASA

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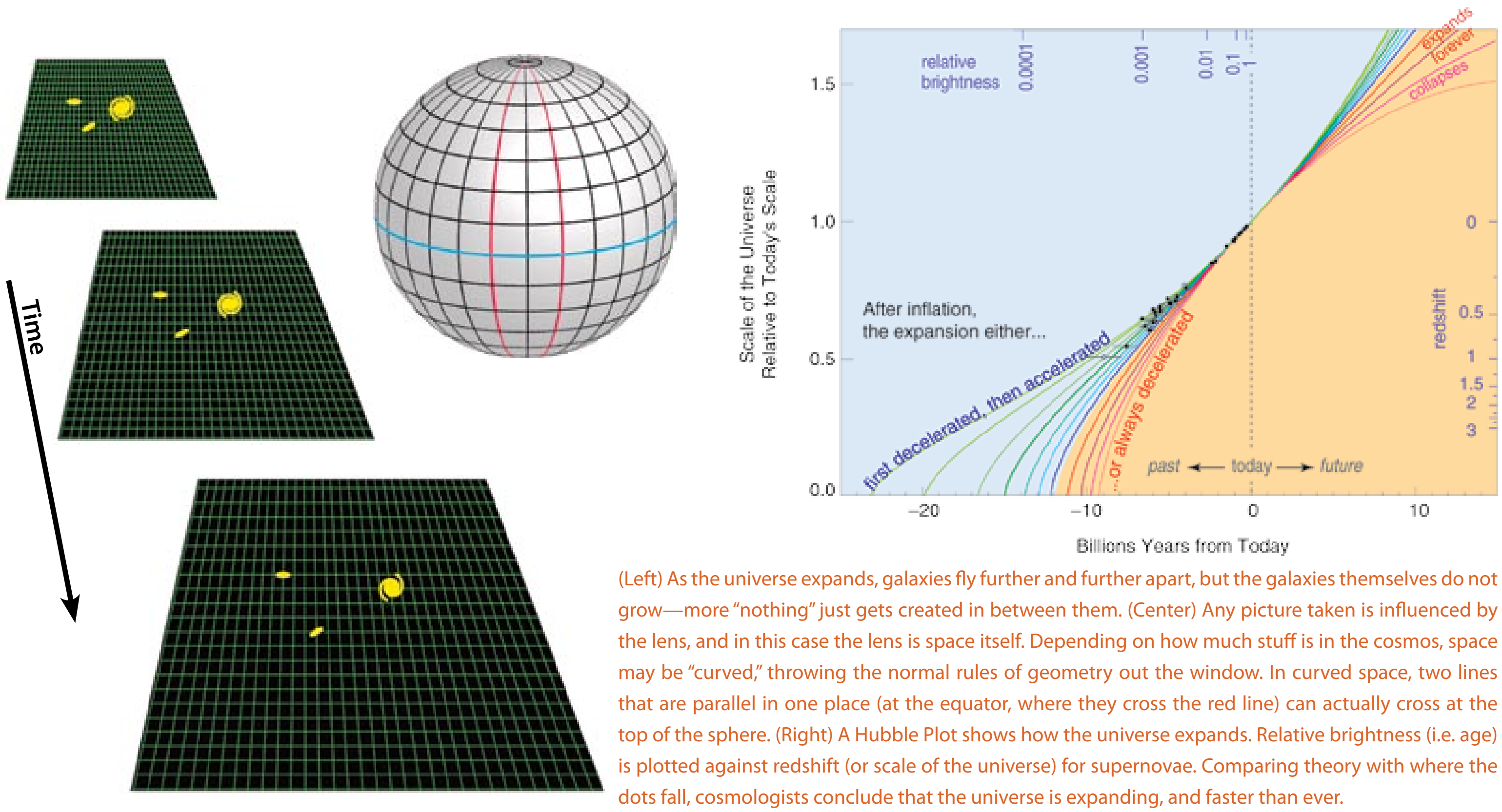
*Hubble counted Charlie Chaplin, Aldous Huxley, and William Randolph Hearst as his friends, and the Hooker telescope where he made his observations became a tourist attraction.



(Left) As the universe expands, galaxies fly further and further apart, but the galaxies themselves do not grow—more "nothing" just gets created in between them. (Center) Any picture taken is influenced by the lens, and in this case the lens is space itself. Depending on how much stuff is in the cosmos, space may be "curved," throwing the normal rules of geometry out the window. In curved space, two lines that are parallel in one place (at the equator, where they cross the red line) can actually cross at the top of the sphere. (Right) A Hubble Plot shows how the universe expands. Relative brightness (i.e. age) is plotted against redshift (or scale of the universe) for supernovae. Comparing theory with where the dots fall, cosmologists conclude that the universe is expanding, and faster than ever.

occupy some unique and central position in the universe—a conclusion many theologians might embrace. Hubble realized that this issue is moot if the entire universe is expanding. "The picture isn't that stuff is exploding away from us," explains Berkeley physics professor Lawrence Hall, but that "everything is moving away from everything." Hall, who has studied the interface between cosmology and particle physics for years, points out that "nothing's really moving. More space is just being created between neighboring galaxies. It's more like space is being stretched." "As a photon travels through the universe that's stretching" explains Perlmutter "its wavelength gets stretched in exact proportion to the stretch of the universe". This accounts for the shifts in wavelength measured by Hubble. "Redshift on a Hubble plot is telling us very directly the total expansion of the universe since the light left a star." In this way, Hubble's plot was the first history of the universe's expansion over time.

Standard candles

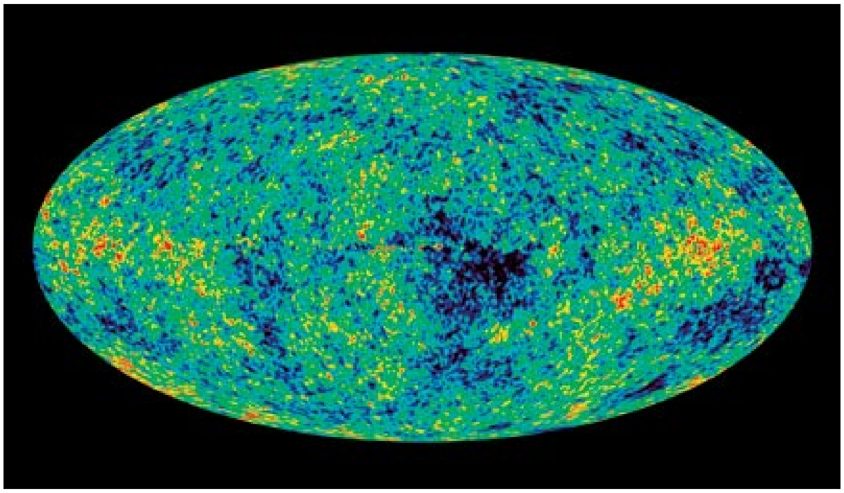
While Hubble's discovery was a fundamental insight into the nature of the universe, his techniques were crude by modern standards. By comparing a celestial object's intrinsic brightness to its brightness as measured here on Earth, astronomers can tell how far away the object is. Since Hubble had only rough estimates of the actual intensities of the galaxies he was measuring, he did not know their exact distances. The problem, Perlmutter jokes, "is that there are no light bulbs in the sky conveniently stamped, '60 watts'."

Astrophysicists have recently discovered that a certain kind of supernova does have a known absolute brightness—the astronomical equivalent of a 60-watt standard. "When stars with masses similar to the sun use up their fuel," explains Perlmutter, "they ordinarily spend the rest of eternity as a white dwarf, gradually cooling away. But if a white dwarf orbits a neighboring star close enough that the star's solar wind falls on the dwarf, it will build up mass little by little until it reaches just enough mass for a runaway nuclear explosion." Such explosions are known as type Ia supernovae and always have a similar intensity because they always occur when the star reaches a very specific threshold mass.Termed "standard candles" by cosmologists, type Ia's have allowed the measurement of the Hubble constant in recent years with unprecedented precision.

The universe quickens its pace

The Hubble constant is actually a bit of a misnomer. "It should never have been called the Hubble constant," laments Hall. "I would call it the Hubble function, and the Hubble function is a function of time.” Conventional reasoning suggests that as the universe expands, gravity should pull it back inward, thus slowing its expansion. This means that the Hubble constant—the speed of the universe’s expansion—should be smaller today than it was in the past. Perlmutter’s team set out to measure this deceleration over a decade ago using these type Ia “standard candles” to survey very distant, and hence ancient galaxies.

Perlmutter recalls that “we thought we would see the supernovae brighter than predicted by Hubble’s Law. By seeing how much brighter would tell us how much the universe was slowing down.” Surprisingly, his group at LBL as well as a competing group from Harvard, saw exactly the opposite. “They were even fainter than what you would expect for a universe slowing at all, and in fact were so faint that they could only come from a universe that is speeding up.”



Our most ancient picture of the universe: the Cosmic Microwave Background (CMB). In 2003, NASA and Princeton scientists published an all-sky map of the CMB taken with the WMAP satellite. The mottled pattern holds the key to many secrets of the cosmos, like whether it’s flat or curved.

The most popular way to account for this newfound acceleration has been to revive Einstein’s cosmological constant. Instead of casting it as a fudge-factor to make the equations spit out a static universe, the cosmological constant has been reborn as a new, unseen form of energy. This dark energy exerts a strong negative pressure that counters the inward pull of gravity. In order to match the rate of expansion that the LBL and Harvard teams independently measured, the unexplained dark energy must account for two-thirds of the total energy content of the universe.

The circumstantial evidence

Perlmutter’s supernova data are not the only measurements to suggest that dark energy exists. Several forms of corroborating evidence, including recent measurements of the Cosmic Microwave Background (CMB) and of the large scale structure of the universe, have since emerged. The CMB is a lingering remnant of the birth of atomic matter about 400,000 years after the Big Bang. These freshly cooled atoms gave off light whose wavelength has since stretched into the microwave region of the spectrum as the universe has expanded. These microwaves comprise our most ancient picture of the 14 billion year old universe. Put another way: if the universe were an eighty year old man, the CMB would be a photograph of him taken just eighteen hours after birth.

Berkeley physicist Paul Richards used the MAXIMA telescope, floating on a balloon high above much of Earth’s atmosphere, to measure the CMB and get a glimpse of the universe’s baby pictures. Richards describes observing the CMB as “looking at a fog across the bay. As you look further and further away, further and further back in time…you only see its surface and nothing within.” The light coming from this surface is remarkably uniform, marred only by very slight fluctuations—ripples caused by the Big Bang itself. The nature of the fluctuations can tell physicists about the geometry of the space they travel through.

According to Einstein, gravitational forces arise because matter and energy alter the geometry of the space in which they reside. An empty, non-expanding space will be “flat”, meaning it follows all the rules taught in high school geometry, such as parallel lines never crossing. However, when space is filled with massive objects or energy, it becomes “curved” and many of these familiar rules of geometry break down. Even if an expanding universe contains mass and energy, it can still be flat, provided that it has a very specific density. This “critical density” describes a universe just barely light enough to avoid an eventual collapse.

Examining the CMB closely reveals that the universe is flat. Richards explains, “you can judge the distance to a car down the street because it looks smaller than it really is and how much smaller tells you how far away it is. But if you put

EXPANSION AND SPHERE GRAPHICS BY C. EMRICH AND R. O’BRIENT
HUBBLE PLOT COURTESY: LAWRENCE BERKELEY NATIONAL LAB

IMAGE COURTESY: NASA/WMAP TEAM

a lens in front of your eye, it will distort the image, making it look smaller or larger. But that's exactly what a curved space does to light, it lenses it." Curved space will also distort the polka-dot pattern in the CMB. Because scientists know the size of these spots in the CMB and the distance to them, they can calculate how large the fluctuations should appear when seen from Earth: for a flat universe, they should be the size of a full moon. But the size they actually appear depends on how curved the universe is, because a highly curved universe would magnify or de-magnify these dots from their size in a flat universe. The MAXIMA telescope was one of the first to successfully measure that the size of these fluctuations is indeed the correct size for a flat universe, and this has since been confirmed by satellite measurements.

Richards' measurements of the CMB and of these fluctuations imply that our universe has a flat geometry. Einstein's theory of general relativity says that a universe with mass and energy (like our own) can only be flat if the density of that mass and energy is equal to one critical value, known as the 'critical density'. But all the known energy and mass density of the universe was found to be too small to account for this critical density. The remaining slice of the pie is now thought to be comprised of dark energy.

A third line of evidence, the mapping of the large-scale structure of the universe, independently suggests the presence of dark energy. By focusing their telescopes on large, distant areas of the sky, cosmologists are able to measure the number of galaxies and their clustering and distribution across the largest scales of the universe.

Their experimental observations can only accommodate a universe with massive particles that account for 30% of the critical density. In close agreement with Perlmutter's supernova data, most cosmologists believe that the missing 70% of the universe's density can be accounted for by dark energy. Evidence from all three types of measurements—supernovae, CMB, and the structure of galaxy clusters—all converge on the same conclusion: the cosmos must be 70% dark energy.

The Hubble Space Telescope spends much of its time hunting for the type Ia supernovae that can tell physicists how fast the universe is expanding.

IMAGE COURTESY: NASA

What is dark energy?

If so many measurements suggest that the universe is permeated with dark energy, then what exactly is it? Hall admits, "we don't have a clue." Physicists do, however, have a few guesses. Two such guesses, vacuum energy and quintessence, are based on so-called "vacuum fluctuations." Even the best vacuum isn't really empty. Particles are continually popping into and out of existence. These are vacuum fluctuations—the short-lived creation and destruction of matter-antimatter particle pairs in a vacuum. While this might sound like science fiction, such fluctuations create measurable effects in laboratory experiments on Earth. At first, vacuum energy appears to be a good candidate for the source of dark energy. The only hitch is that estimates of vacuum energies from known matter-antimatter pairs are way too big: 10^{120} times too big. That much 'extra' energy would have long since torn apart our universe. Daunted, but not beaten, particle theorists are hard at work looking for new exotic particles with vacuum energies small enough to drive the more gentle acceleration we observe in the sky.

Quintessence, or the 'fifth essence', was originally proposed by ancient Greek philosophers to explain how the heavens were held together. Today particle physicists use the word to describe a hypothetical energy field that varies over time and space, holding the heavens together. This hypothetical "quintessence field" is made up of many small energy fields generated by vacuum fluctuations. Theorists predict that the small fields should oscillate over time like a ball rolling up and down the sides of a bowl; the pace at which the field oscillates determines the rate of the vacuum fluctuations. The universe-spanning quintessence field is oscillating so slowly that it has yet to complete one full cycle during the 14 billion years since the Big Bang. A quintessence field would still oscillate like the ball in a bowl, except this bowl would look more like a giant plate with a very gentle slope that allows for what Hall describes as a "slow roll down to the bottom of the well."

The quintessence field theory, like the vacuum energy theory, uses the existence of vacuum fluctuations to balance the universal energy sheet. The two theories do, however, make very different predictions: while vacuum energy-driven acceleration would be constant, quintessence-driven acceleration would dissipate over time as the metaphorical ball rolls into the bottom of the well.

The next step

In Perlmutter's eyes, "the theorists are still in brainstorming mode." That hasn't discouraged his group from pushing ahead with the next round of supernova measurements. "We can compute what the recent history of the expansion of the universe would look like, and it does indeed differ for a cosmological constant, or a quintessence field, or other theories." Today the density of dark energy is far greater than that of matter because while matter has been spreading out as the universe expands, the density of dark energy has remained constant. Peering back in time—when the universe was much smaller—there must have been a point when the density of matter and dark energy were equal. The time of this balance point would differ depending on whether dark energy is caused by vacuum energy, quintessence, or some other, more exotic source. The current goal of Perlmutter's group is to precisely characterize the expansion rate near this time of equal densities. This will be crucial in determining the true origin of dark energy.

Perlmutter and his team are engaged in a constant battle to find a signal—light from supernovae—after it has passed through interstellar dust. "The challenge behind this next round of measurements," according to Perlmutter, is to understand how "the dust in the supernovae host galaxies… attenuates the brightness of the explosions." Their latest trick has been to sidestep the problem entirely by looking for dust-free galaxies. "We've chosen to focus on clusters of galaxies, because in clusters, you mostly have older elliptical galaxies, and in older galaxies you have more Type Ia supernova and almost no dust."

To search for these supernovae, Perlmutter's team has cornered nearly a quarter of the remaining lifetime of the Hubble Space Telescope. Launched in 1990 and orbiting 375 miles above Earth, the Hubble telescope will likely continue functioning only until 2011 without a service mission from the recently re-grounded Space Shuttle fleet. This powerful telescope should be able to find tens to hundreds of type Ia supernovae in the next few years. Looking even further down the road, Perlmutter's team hopes to launch a dedicated satellite called SNAP (SuperNova Acceleration Probe) that will find hundreds to thousands of supernovae each year and will perhaps allow cosmologists to precisely characterize the properties of dark energy.

One hundred years ago, Albert Einstein published his first papers on relativity, radically altering our conceptions of space and time. Today, the struggle to understand cosmic acceleration and the recent development of the theory of dark energy are not only fundamentally challenging our understanding of the laws and origin of the universe, but are also hinting at its ultimate fate. As the Hubble Space Telescope spends its final days squinting at some of the universe's most ancient galaxies, it's becoming increasingly clear that the fate of the universe ultimately hinges upon the shadowy physics of the vacuous expanse between the stars.

Roger O'Brient *is a graduate student in physics.*

Want to know more?
Check out the Supernova Cosmology Project at LBL: Supernova.lbl.gov
And the next generation supernova-hunting telescope, SNAP: snap.lbl.gov

background.uchicago.edu/~whu/physics/physics.html

"Supernovae, Dark Energy, and the Accelerating Universe": Saul Perlmutter, *Physics Today* (April 2003) pp. 53–60.