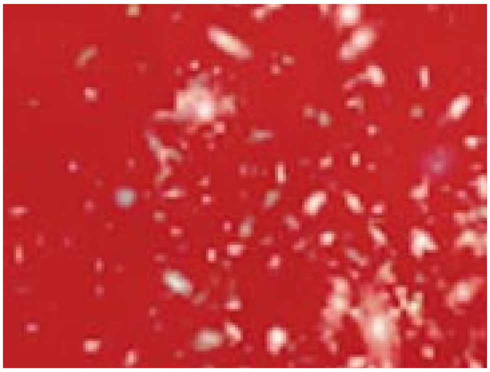
The Quintessential

The universe has recently been commandeered by an invisible energy field, which is causing its expansion to accelerate outward

Universe


DON DIXON

MEET THE NEW BOSS

On scales where even galaxies are mere smidgens, a bizarre "dark energy" now appears to call the shots.

by Jeremiah P. Ostriker and Paul J. Steinhardt

Is it all over but the shouting? Is the cosmos understood aside from minor details? A few years ago it certainly seemed that way. After a century of vigorous debate, scientists had reached a broad consensus about the basic history of the universe. It all began with gas and radiation of unimaginably high temperature and density. For 15 billion years, it has been expanding and cooling. Galaxies and other complex structures have grown from microscopic seeds—quantum fluctuations—that were stretched to cosmic size by a brief period of "inflation." We had also learned that only a small fraction of matter is composed of the normal chemical elements of our everyday experience. The majority consists of so-called dark matter, primarily exotic elementary particles that do not interact with light. Plenty of mysteries remained, but at least we had sorted out the big picture.

Or so we thought. It turns out that we have been missing most of the story. Over the past five years, observations have convinced cosmologists that the chemical elements and the dark matter, combined, amount to less than half the content of the universe. The bulk is a ubiquitous "dark energy" with a strange and remarkable feature: its gravity does not attract. It repels. Whereas gravity pulls the chemical elements and dark matter into stars and galaxies, it pushes the dark energy into a nearly uniform haze that permeates space. The universe is a battleground between the two tendencies, and repulsive gravity is winning. It is gradually overwhelming the attractive force of ordinary matter—causing the universe to accelerate to ever larger rates of expansion, perhaps leading to a new runaway inflationary phase and a totally different future for the universe than most cosmologists envisioned a decade ago.

Until recently, cosmologists have focused simply on proving the existence of dark energy. Having made a convincing case, they are now turning their attention to a deeper problem: Where does the energy come from? The best-known possibility is that the energy is inherent in the fabric of space. Even if a volume of space were utterly empty—without a bit of matter and radiation—it would still contain this energy. Such energy is a venerable notion that dates back to Albert Einstein and his attempt in 1917 to construct a static model of the universe. Like many leading scientists over the centuries, including Isaac Newton, Einstein believed that the universe is unchanging, neither contracting nor expanding. To coax stagnation from his general theory of relativity, he had to introduce vacuum energy or, in his terminology, a cosmological constant. He adjusted the value of the constant so that its gravitational repulsion would exactly counterbalance the gravitational attraction of matter.

Later, when astronomers established that the universe is expanding, Einstein regretted his delicately tuned artifice, calling it his greatest blunder. But perhaps his judgment was too hasty. If the cosmological constant had a slightly larger value than Einstein proposed, its repulsion would exceed the attraction of matter, and cosmic expansion would accelerate.

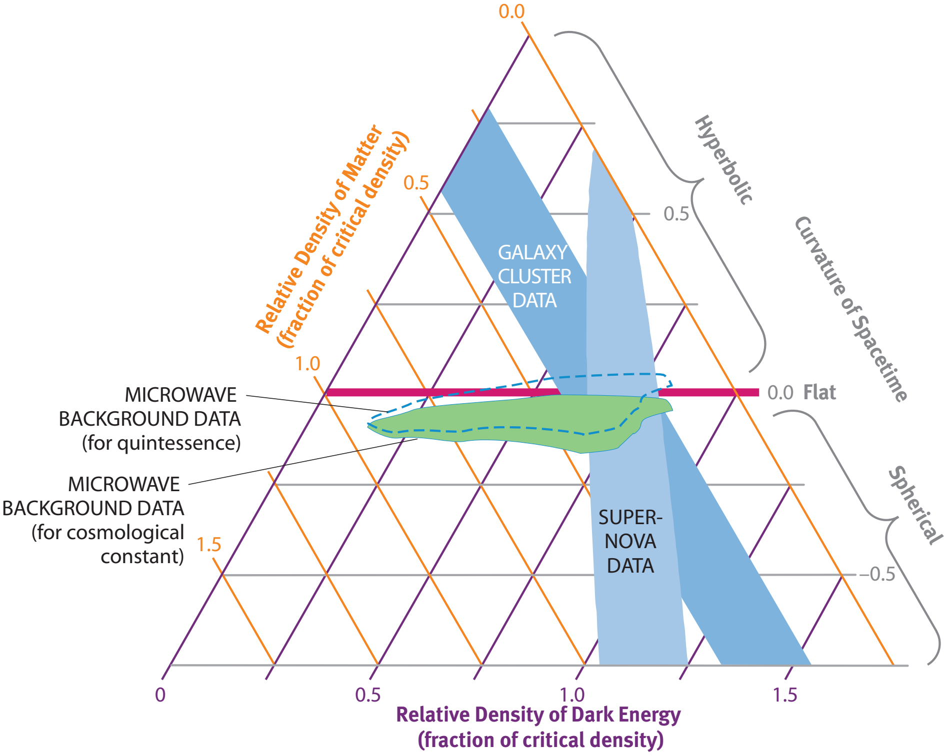
Many cosmologists, though, are now leaning toward a different idea, known as quintessence. The translation is "fifth element," an allusion to ancient Greek philosophy, which suggested that the universe is composed of earth, air, fire and water, plus an ephemeral substance that prevents the moon and planets from falling to the center of the celestial sphere. Three years ago Robert R. Caldwell, Rahul Dave and one of us (Steinhardt), all then at the University of Pennsylvania, reintroduced the term to refer to a dynamical quantum field, not unlike an electrical or magnetic field, that gravitationally repels.

The dynamism is what cosmologists find so appealing about quintessence. The biggest challenge for any theory of dark energy is to explain the inferred amount of the stuff—not so much that it would have interfered with the formation of stars and galaxies in the early universe but just enough that its effect can now be felt. Vacuum energy is completely inert, maintaining the same density for all time. Consequently, to explain the amount of dark energy today, the value of the cosmological constant would have to be fine-tuned at the creation of the universe to have the proper value—which makes it sound rather like a fudge factor. In contrast, quintessence interacts with matter and evolves with time, so it might naturally adjust itself to reach the observed value today.

Two Thirds of Reality

Distinguishing between these two options is critically important for physics. Particle physicists have depended on high-energy accelerators to discover new forms of energy and matter. Now the cosmos has revealed an unanticipated type of energy, too thinly spread and too weakly interacting for accelerators to probe. Whether the energy is inert or dynamical may be cru-

DON DIXON



COSMIC TRIANGLE

In this graph of cosmological observations, the axes represent possible values of three key characteristics of the universe. If the universe is flat, as inflationary theory suggests, the different types of observations (*colored areas*) and the zero-curvature line (*red line*) should overlap. At present, the microwave background data produce a slightly better overlap if dark energy consists of quintessence (*dashed outline*) rather than the cosmological constant (*green area*).

JANA BRENNING; SOURCE: PAUL J. STEINHARDT

cial to developing a fundamental theory of nature. Particle physicists are discovering that they must keep a close eye on developments in the heavens as well as in the accelerator laboratory.

The case for dark energy has been building brick by brick for nearly a decade. The first brick was a thorough census of all matter in galaxies and galaxy clusters using a variety of optical, x-ray and radio techniques. The unequivocal conclusion was that the total mass in chemical elements and dark matter accounts for only about one third of the quantity that most theorists expected—the so-called critical density.

Many cosmologists took this as a sign that the theorists were wrong. In that case, we would be living in an ever expanding universe where space is curved hyperbolically, like the horn on a trumpet [see "Inflation in a Low-Density Universe," by Martin A. Bucher and David N. Spergel; Scientific American, January 1999]. But this interpretation has been put to rest by measurements of hot and cold spots in the cosmic microwave background radiation, whose distribution has shown that space is flat and that the total energy density equals the critical density. Putting the two observations together, simple arithmetic dictates the necessity for an additional energy component to make up the missing two thirds of the energy density.

Whatever it is, the new component must be dark, neither absorbing nor emitting light, or else it would have been noticed long ago. In that way, it resembles dark matter. But the new component—called dark energy—differs from dark matter in one major respect: it must be gravitationally repulsive. Otherwise it would be pulled into galaxies and clusters, where it would affect the motion of visible matter. No such influence is seen. Moreover, gravitational repulsion resolves the "age crisis" that plagued cosmology in the 1990s. If one takes the current measurements of the expansion rate and assumes that the expansion has been decelerating, the age of the universe is less than 12 billion years.

Yet evidence suggests that some stars in our galaxy are 15 billion years old. By causing the expansion rate of the universe to accelerate, repulsion brings the inferred age of the cosmos into agreement with the observed age of celestial bodies [see "Cosmological Antigravity," by Lawrence M. Krauss; Scientific American, January 1999].

The potential flaw in the argument used to be that gravitational repulsion should cause the expansion to accelerate, which had not been observed. Then, in 1998, the last brick fell into place. Two independent groups used measurements of distant supernovae to detect a change in the expansion rate. Both groups concluded that the universe is accelerating and at just the pace predicted [see "Surveying Space-time with Supernovae," by Craig J. Hogan, Robert P. Kirshner and Nicholas B. Suntzeff; Scientific American, January 1999].

All these observations boil down to three numbers: the average density of matter (both ordinary and dark), the average density of dark energy, and the curvature of space. Einstein's equations dictate that the three numbers add up to the critical density. The different possible combinations of the numbers can be succinctly represented on a triangular plot [*see illustration at left*]. The three distinct sets of observations—matter census, cosmic microwave background, and supernovae—correspond to strips inside the triangle. Remarkably, the three strips overlap at the same position, which makes a compelling case for dark energy.

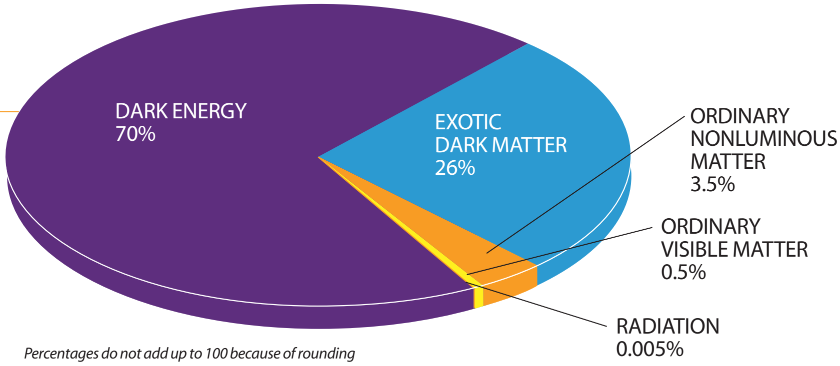
From Implosion to Explosion

Our everyday experience is with ordinary matter, which is gravitationally attractive, so it is difficult to envisage how dark energy could gravitationally repel. The key feature is that its pressure is negative. In Newton's law of gravity, pressure plays no role; the strength of gravity depends only on mass. In Einstein's law of gravity, however, the strength of gravity depends not just on mass but also on other forms of energy and on pressure. In this way, pressure has two effects: direct (caused by the action of the pressure on surrounding material) and indirect (caused by the gravitation that the pressure creates).

The sign of the gravitational force is determined by the algebraic combination of the total energy density plus three times the pressure. If the pressure is positive, as it is for radiation, ordinary matter and dark matter, then the combination is positive and gravitation is attractive. If the pressure is sufficiently negative, the combination is negative and gravitation is repulsive. To put it quantitatively, cosmologists consider the ratio of pressure to energy density, known as

■ RECIPE FOR THE UNIVERSE

The main ingredient of the universe is “dark energy,” which consists of either the cosmological constant or the quantum field known as quintessence. The other ingredients are dark matter composed of exotic elementary particles, ordinary matter (both nonluminous and visible), and a trace amount of radiation.



Percentages do not add up to 100 because of rounding

JANA BRENNING

the equation of state, or w. For an ordinary gas, w is positive and proportional to the temperature. But for certain systems, w can be negative. If it drops below –⅓, gravity becomes repulsive.

Vacuum energy meets this condition (provided its density is positive). This is a consequence of the law of conservation of energy, according to which energy cannot be destroyed. Mathematically the law can be rephrased to state that the rate of change of energy density is proportional to $w + 1$. For vacuum energy—whose density, by definition, never changes—this sum must be zero. In other words, w must equal precisely –1. So the pressure must be negative.

What does it mean to have negative pressure? Most hot gases have positive pressure; the kinetic energy of the atoms and radiation pushes outward on the container. Note that the direct effect of positive pressure—to push—is the opposite of its gravitational effect—to pull. But one can imagine an interaction among atoms that overcomes the kinetic energy and causes the gas to implode. The implosive gas has negative pressure. A balloon of this gas would collapse inward, because the outside pressure (zero or positive) would exceed the inside pressure (negative). Curiously, the direct effect of negative pressure—implosion—can be the opposite of its gravitational effect—repulsion.

Improbable Precision

The gravitational effect is tiny for a balloon. But now imagine filling all of space with the implosive gas. Then there is no bounding surface and no external pressure. The gas still has negative pressure, but it has nothing to push against, so it exerts no direct effect. It has only the gravitational effect—namely, repulsion. The repulsion stretches space, increasing its volume and, in turn, the amount of vacuum energy. The tendency to stretch is therefore self-reinforcing. The universe expands at an accelerating pace. The growing vacuum energy comes at the expense of the gravitational field.

These concepts may sound strange, and even Einstein found them hard to swallow. He viewed the static universe, the original motivation for vacuum energy, as an unfortunate error that ought to be dismissed. But the cosmological constant, once introduced, would not fade away. Theorists soon realized that quantum fields possess a finite amount of vacuum energy, a manifestation of quantum fluctuations that conjure up pairs of “virtual” particles from scratch. An estimate of the total vacuum energy produced by all known fields predicts a huge amount—120 orders of magnitude more than the energy density in all other matter. That is, though it is hard to picture, the evanescent virtual particles should contribute a positive, constant energy density, which would imply negative pressure. But if this estimate were true, an acceleration of epic proportions would rip apart atoms, stars and galaxies. Clearly, the estimate is wrong. One of the major goals of unified theories of gravity has been to figure out why.

One proposal is that some heretofore undiscovered symmetry in fundamental physics results in a cancellation of large effects, zeroing out the vacuum energy. For example, quantum fluctuations of virtual pairs of particles contribute positive energy for particles with half-integer spin (like quarks and electrons) but negative energy for particles with integer spin (like photons). In standard theories, the cancellation is inexact, leaving behind an unacceptably large energy density. But physicists have been exploring models with so-called supersymmetry, a relation between the two particle types that can lead to a precise cancellation. A serious flaw, though, is that supersymmetry would be valid only at very high energies. Theorists are working on a way of preserving the perfect cancellation even at lower energies.

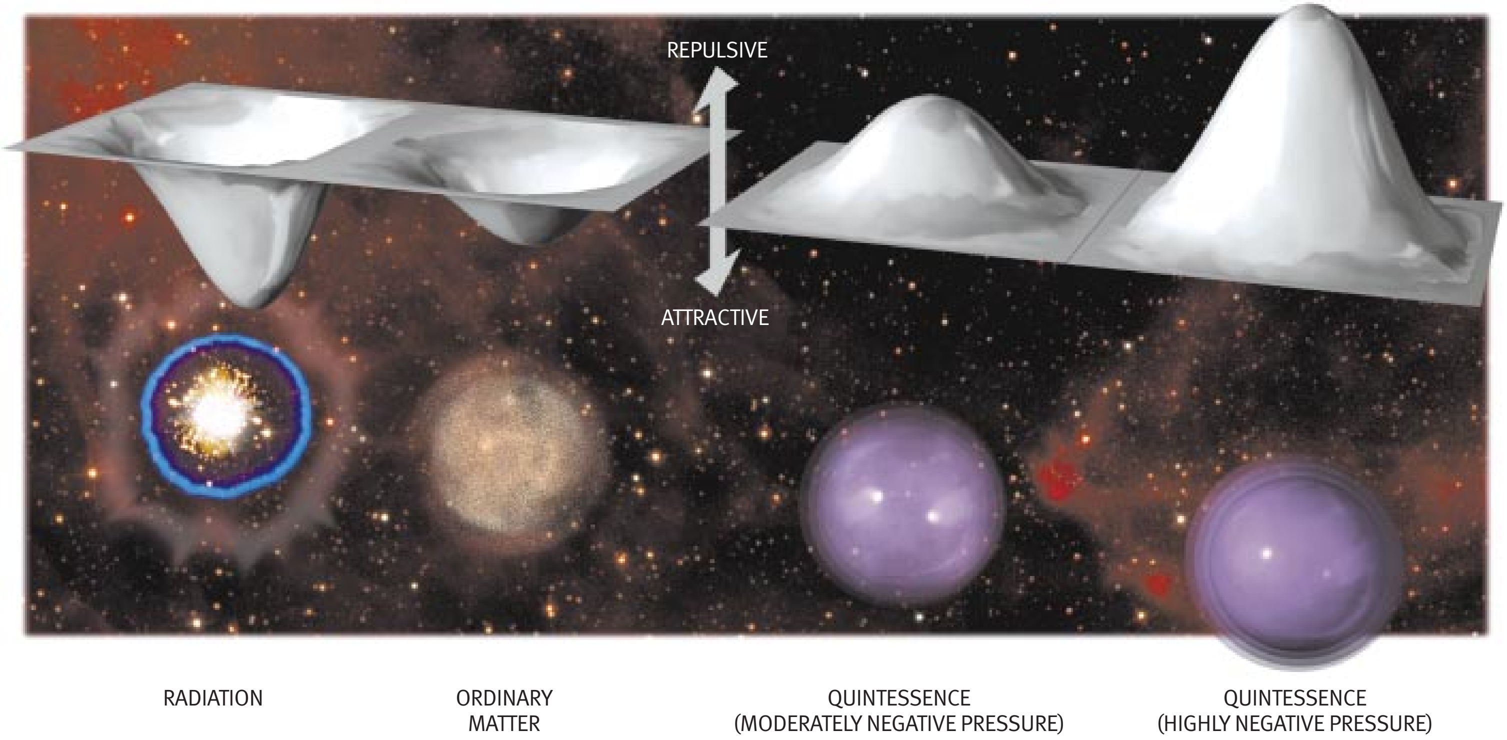
Another thought is that the vacuum energy is not exactly nullified after all. Perhaps there is a cancellation mechanism that is slightly imperfect. Instead of making the cosmological constant exactly zero, the mechanism only cancels to 120 decimal places. Then the vacuum energy could constitute the missing two thirds of the universe. That seems bizarre, though. What mechanism could possibly work with such precision? Although the dark energy represents a huge amount of mass, it is spread so thinly that its energy is less than four electron volts per cubic millimeter—which, to a particle physicist, is unimaginably low. The weakest known force in nature involves an energy density 10^{50} times greater.

Extrapolating back in time, vacuum energy gets even more paradoxical. Today matter and dark energy have comparable average densities. But billions of years ago, when they came into being, our universe was the size of a grapefruit, so matter was 100 orders of magnitude denser. The cosmological constant, however, would have had the same value as it does now. In other words, for every 10^{100} parts matter, physical processes would have created one part vacuum energy—a degree of exactitude that may be reasonable in a mathematical idealization but that seems ludicrous to expect from the real world. This need for almost supernatural fine-tuning is the principal motivation for considering alternatives to the cosmological constant.

Fieldwork

Fortunately, vacuum energy is not the only way to generate negative pressure. Another means is an energy source that, unlike vacuum energy, varies in space and time—a realm of possibilities that goes under the rubric of quintessence. For quintessence, w has no fixed value, but it must be less than –⅓ for gravity to be repulsive.

Quintessence may take many forms. The simplest models propose a quantum field whose energy is varying so slowly that it looks, at first glance, like a constant vacuum energy. The idea is bor-



■ THE POWER OF POSITIVE (AND NEGATIVE) THINKING

Whether a lump of energy exerts a gravitationally attractive or repulsive force depends on its pressure. If the pressure is zero or positive, as it is for radiation or ordinary matter, gravity is attractive. (The downward dimples represent the potential energy wells.) Radiation has greater pressure, so its gravity is more attractive. For quintessence, the pressure is negative and gravity is repulsive (the dimples become hills).

DON FOLEY; SOURCE: ROBERT R. CALDWELL *Dartmouth College* AND PAUL J. STEINHARDT

rowed from inflationary cosmology, in which a cosmic field known as the inflaton drives expansion in the very early universe using the same mechanism [see "The Inflationary Universe," by Alan H. Guth and Paul J. Steinhardt; Scientific American, May 1984]. The key difference is that quintessence is much weaker than the inflaton. This hypothesis was first explored a decade ago by Christof Wetterich of the University of Heidelberg and by Bharat Ratra, now at Kansas State University, and P. James E. Peebles of Princeton University.

In quantum theory, physical processes can be described in terms either of fields or of particles. But because quintessence has such a low energy density and varies so gradually, a particle of quintessence would be inconceivably lightweight and large—the size of a supercluster of galaxies. So the field description is rather more useful. Conceptually, a field is a continuous distribution of energy that assigns to each point in space a numerical value known as the field strength. The energy embodied by the field has a kinetic component, which depends on the time variation of the field strength, and a potential component, which depends only on the value of the field strength. As the field changes, the balance of kinetic and potential energy shifts.

In the case of vacuum energy, recall that the negative pressure was the direct result of the conservation of energy, which dictates that any variation in energy density is proportional to the sum of the energy density (a positive number) and the pressure. For vacuum energy, the change is zero, so the pressure must be negative. For quintessence, the change is gradual enough that the pressure must still be negative, though somewhat less so. This condition corresponds to having more potential energy than kinetic energy.

Because its pressure is less negative, quintessence does not accelerate the universe as strongly as vacuum energy does. Ultimately, this will be how observers decide between the two. If anything, quintessence is more consistent with the available data, but for now the distinction is not statistically significant. Another difference is that, unlike vacuum energy, the quintessence field may undergo all kinds of complex evolution. The value of w may be positive, then negative, then positive again. It may have different values in different places. Although the nonuniformity is thought to be small, it may be detectable by studying the cosmic microwave background radiation.

A further difference is that quintessence can be perturbed. Waves will propagate through it just as sound waves can pass through the air. In the jargon, quintessence is "soft." Einstein's cosmological constant is, in contrast, stiff—it cannot be pushed around. This raises an interesting issue. Every known form of energy is soft to some degree. Perhaps stiffness is an idealization that cannot exist in reality, in which case the cosmological constant is an impossibility. Quintessence with w near -1 may be the closest reasonable approximation.

Quintessence on the Brane

Saying that quintessence is a field is just the first step in explaining it. Where would such a strange field come from? Particle physicists have explanations for phenomena from the structure of atoms to the origin of mass, but quintessence is something of an orphan. Modern theories of elementary particles include many kinds of fields that might have the requisite behavior, but not enough is known about their kinetic and potential energy to say which, if any, could produce negative pressure today.

An exotic possibility is that quintessence springs from the physics of extra dimensions. Over the past few decades, theorists have been exploring string theory, which may combine general relativity and quantum mechanics in a unified theory of fundamental forces. An important feature of string models is that they predict 10 dimensions. Four of these are our familiar three spatial dimensions, plus time. The remaining six must be hidden. In some formulations, they are curled up like a ball whose radius is too small to be detected (at least with present instruments). An alternative idea is found in a recent extension of string theory, known as M-theory, which adds an 11th dimension: ordinary matter is confined to two three-dimensional surfaces, known as branes (short for membranes), separated by a microscopic gap along the 11th dimension [see "The Universe's Unseen Dimensions," by Nima Arkani-Hamed, Savas Dimopoulos and Georgi Dvali; Scientific American, August 2000].

We are unable to see the extra dimensions, but if they exist, we should be able to perceive them indirectly. In fact, the presence of curled-up dimensions or nearby branes would act just like a field. The numerical value that the field assigns to each point in space could correspond to the radius or gap distance. If the radius or gap changes slowly as the universe expands, it could exactly mimic the hypothetical quintessence field.

What a Coincidence

Whatever the origin of quintessence, its dynamism could solve the thorny problem of fine-tuning. One way to look at this issue is to ask, Why has cosmic acceleration begun at this particular moment in cosmic history? Created when the universe was 10^{-35} second old, dark energy must have remained in the shadows for nearly 10 billion years—a factor of more than 10^{50} in age. Only then, the data suggest, did it overtake matter and cause the universe to begin accelerating. Is it not a coincidence that, just when thinking beings evolved, the universe suddenly shifted into overdrive? Somehow the fates of matter and of dark energy seem to be intertwined. But how?

If the dark energy is vacuum energy, the coincidence is almost impossible to account for. Some researchers, including Martin Rees of the University of Cambridge and Steven Weinberg of the University of Texas at Austin, have pursued an anthropic explanation. Perhaps our universe is just one among a multitude of universes, in each of which the vacuum energy takes on a different value. Universes with vacuum energy much greater than four electron volts per cubic millimeter might be more common, but they expand too rapidly to form stars, planets or life. Universes with much smaller values might be very rare. Our universe would have the optimal value. Only in this "best of all worlds" could there exist intelligent beings capable of contemplating the nature of the universe. But physicists disagree whether the anthropic argument constitutes an acceptable explanation [see "Exploring Our Universe and Others," by Martin Rees; Scientific American, December 1999].

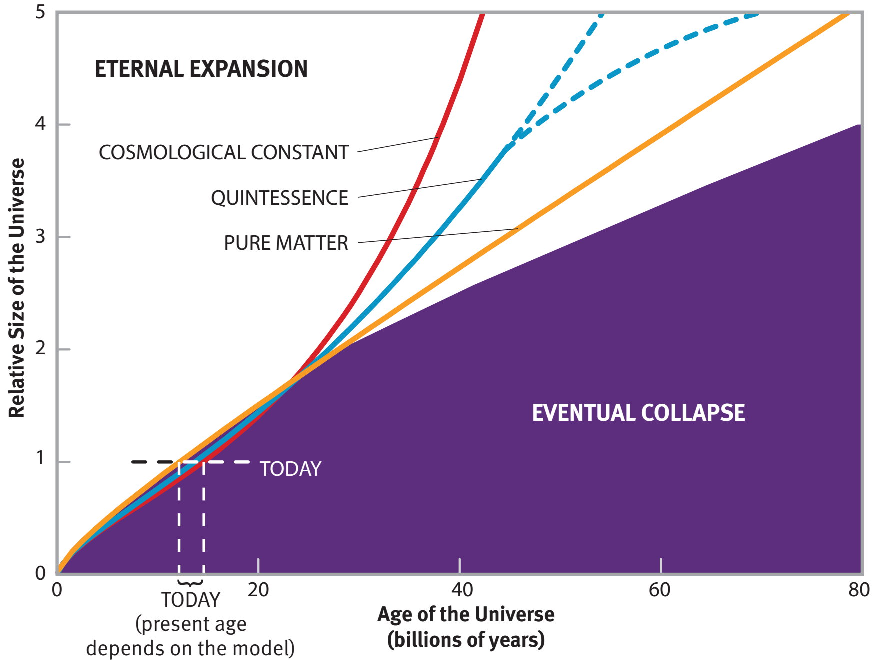
A more satisfying answer, which could involve a form of quintessence known as a tracker field, was studied by Ratra and Peebles and by Steinhardt, Ivaylo Zlatev and Limin Wang of the University of Pennsylvania. The equations that describe tracker fields have classical attractor behavior like that found in some chaotic systems. In such systems, motion converges to the same result for a wide range of initial conditions. A marble put into an empty bathtub, for example, ultimately falls into the drain whatever its starting place.

Similarly, the initial energy density of the tracker field does not have to be tuned to a certain value, because the field rapidly adjusts itself to that value. It locks into a track on which its energy density remains a nearly constant fraction of the density of radiation and matter. In this sense, quintessence imitates matter and radiation, even though its composition is wholly different. The mimicking occurs because the radiation and matter density determine the cosmic expansion rate, which, in turn, controls the rate at which the quintessence density changes. On closer inspection, one finds that the fraction is slowly growing. Only after many millions or billions of years does quintessence catch up.

So why did quintessence catch up when it did? Cosmic acceleration could just as easily have commenced in the distant past or in the far future, depending on the choices of constants in the tracker-field theory. This brings us back to the coincidence. But perhaps some event in the relatively recent past unleashed the acceleration. Steinhardt, along with Christian Armendáriz Picon and Viatcheslav Mukhanov of the Ludwig Maximilians University in Munich, has proposed one such recent event: the

■ GROWING PAINS

The universe expands at different rates depending on which form of energy predominates. Matter causes the growth to decelerate, whereas the cosmological constant causes it to accelerate. Quintessence is in the middle: it forces the expansion to accelerate, but less rapidly. Eventually the acceleration may or may not switch off (*dashed lines*).



JANA BRENNING; SOURCE: ROBERT R. CALDWELL *Dartmouth College* AND PAUL J. STEINHARDT

transition from radiation domination to matter domination.

According to the big bang theory, the energy of the universe used to reside mainly in radiation. As the universe cooled, however, the radiation lost energy faster than ordinary matter did. By the time the universe was a few tens of thousands of years old—a relatively short time ago in logarithmic terms—the energy balance had shifted in favor of matter. This change marked the beginning of the matter-dominated epoch of which we are the beneficiaries. Only then could gravity begin to pull matter together to form galaxies and larger-scale structures. At the same time, the expansion rate of the universe underwent a change.

In a variation on the tracker models, this transformation triggered a series of events that led to cosmic acceleration today. Throughout most of the history of the universe, quintessence tracked the radiation energy, remaining an insignificant component of the cosmos. But when the universe became matter-dominated, the change in the expansion rate jolted quintessence out of its copycat behavior. Instead of tracking the radiation or even the matter, the pressure of quintessence switched to a negative value. Its density held nearly fixed and ultimately overtook the decreasing matter density. In this picture, the fact that thinking beings and cosmic acceleration came into existence at nearly the same time is not a coincidence. Both the formation of stars and planets necessary to support life and the transformation of quintessence into a negative-pressure component were triggered by the onset of matter domination.

Looking to the Future

In the short term, the focus of cosmologists will be to detect the existence of quintessence. It has observable consequences. Because its value of *w* differs from that of vacuum energy, it produces a different rate of cosmic acceleration. More precise measurements of supernovae over a longer span of distances may separate the two cases. Astronomers have proposed two new observatories—the orbiting Supernova Acceleration Probe and the Earth-based Large-Aperture Synoptic Survey Telescope—to resolve the issue. Differences in acceleration rate also produce small differences in the angular size of hot and cold spots in the cosmic microwave background radiation, as the Microwave Anisotropy Probe and Planck spacecraft should be able to detect.

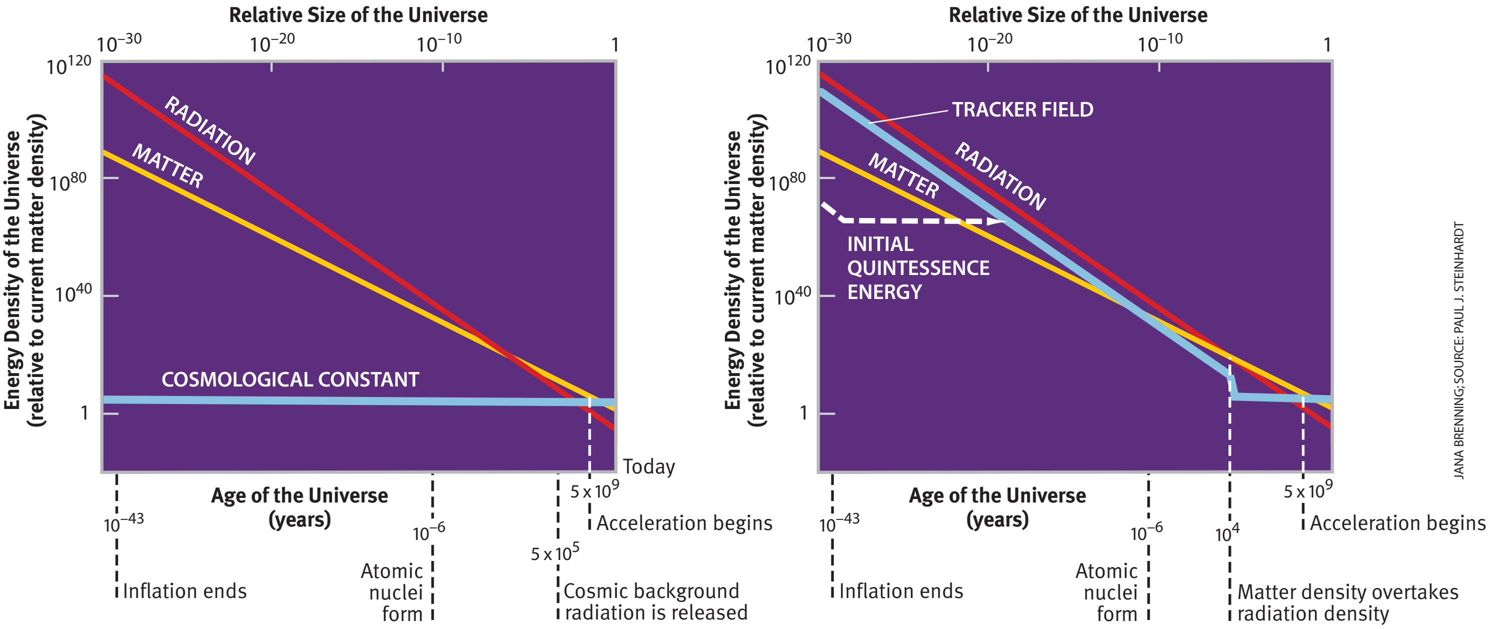
Other tests measure how the number of galaxies varies with increasing redshift to infer how the expansion rate of the universe has changed with time. A ground-based project known as the Deep Extragalactic Evolutionary Probe will look for this effect.

Over the longer term, all of us will be left to ponder the profound implications of these revolutionary discoveries. They lead to a sobering new interpretation of our place in cosmic history. In the beginning (or at least the earliest for which we have any clue), there was inflation, an extended period of accelerated expansion during the first instants after the big bang. Space back then was nearly devoid of matter, and a quintessencelike quantum field with negative pressure held sway. During that period, the universe expanded by a greater factor than it has during the 15 billion years since inflation ended. At the end of inflation, the field decayed to a hot gas of quarks, gluons, electrons, light and dark energy.

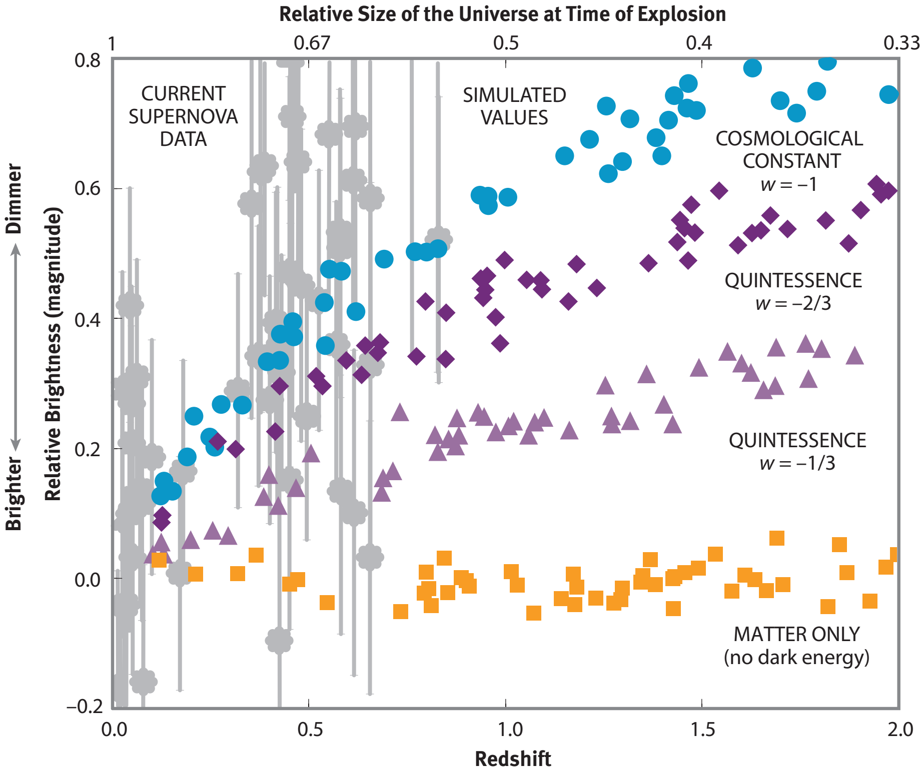
For thousands of years, space was so thick with radiation that atoms, let alone larger structures, could never form. Then matter took control. The next stage—our epoch—has been one of steady cooling, condensation and the evolution of intricate structure of ever increasing size. But this period is coming to an end. Cosmic acceleration is back. The universe as we know it, with shining stars, galaxies and clusters, appears to have been a brief interlude. As acceleration takes hold over the next tens of billions of years, the matter and

■ KEEPING TRACK

If dark energy consists of the cosmological constant, the energy density must be fine-tuned so that it overtakes the matter density in recent history (*left*). For the type of quintessence known as a tracker field (*right*), any initial density value (*dashed line*) converges to a common track (*blue line*) that runs in lockstep with the radiation density until the matter density overtakes it. This causes the tracker density to freeze and to trigger cosmic acceleration.



JANA BRENNING;SOURCE: PAUL J. STEINHARDT



SEEING WILL BE BELIEVING

Supernova data may be one way to decide between quintessence and the cosmological constant. The latter makes the universe speed up faster, so supernovae at a given redshift would be farther away and hence dimmer. Existing telescopes (*data shown in gray*) cannot tell the two cases apart, but the proposed Supernova Acceleration Probe should be able to. The supernova magnitudes predicted by four models are shown in different colors.

JANA BRENNING; SOURCE: IRIT MAOR AND RAM BRUSTEIN *Ben-Gurion University*

energy in the universe will become more and more diluted and space will stretch too rapidly to enable new structures to form. Living things will find the cosmos increasingly hostile [see "The Fate of Life in the Universe," by Lawrence M. Krauss and Glenn Starkman; Scientific American, November 1999]. If the acceleration is caused by vacuum energy, then the cosmic story is complete: the planets, stars and galaxies we see today are the pinnacle of cosmic evolution.

But if the acceleration is caused by quintessence, the ending has yet to be written. The universe might accelerate forever, or the quintessence could decay into new forms of matter and radiation, repopulating the universe. Because the dark-energy density is so small, one might suppose that the material derived from its decay would have too little energy to do anything of interest. Under some circumstances, however, quintessence could decay through the nucleation of bubbles. The bubble interior would be a void, but the bubble wall would be the site of vigorous activity. As the wall moved outward, it would sweep up all the energy derived from the decay of quintessence. Occasionally, two bubbles would collide in a fantastic fireworks display. In the process, massive particles such as protons and neutrons might arise—perhaps stars and planets.

To future inhabitants, the universe would look highly inhomogeneous, with life confined to distant islands surrounded by vast voids. Would they ever figure out that their origin was the homogeneous and isotropic universe we see about us today? Would they ever know that the universe had once been alive and then died, only to be given a second chance?

Experiments may soon give us some idea which future is ours. Will it be the dead end of vacuum energy or the untapped potential of quintessence? Ultimately the answer depends on whether quintessence has a place in the basic workings of nature—the realm, perhaps, of string theory. Our place in cosmic history hinges on the interplay between the science of the very big and that of the very small.

The Authors

JEREMIAH P. OSTRIKER and PAUL J. STEINHARDT, both professors at Princeton University, have been collaborating for the past six years. Their prediction of accelerating expansion in 1995 anticipated the groundbreaking supernova results by several years. Ostriker was one of the first to appreciate the prevalence of dark matter and the importance of hot intergalactic gas. In 2000 he won the U.S. National Medal of Science. Steinhardt was one of the originators of the theory of inflation and the concept of quasicrystals. He reintroduced the term "quintessence" after his youngest son Will and daughter Cindy picked it out from several alternatives.

Further Information

The Observational Case for a Low-Density Universe with a Non-Zero Cosmological Constant. Jeremiah P. Ostriker and Paul J. Steinhardt in *Nature,* Vol. 377, pages 600–602; October 19, 1995. Preprint at xxx.lanl.gov/abs/astro-ph/9505066

Cosmological Imprint of an Energy Component with General Equation of State. Robert R. Caldwell, Rahul Dave and Paul J. Steinhardt in *Physical Review Letters,* Vol. 80, No. 8, pages 1582–1585; February 23, 1998; astro-ph/9708069

Cosmic Concordance and Quintessence. Limin Wang, R. R. Caldwell, J. P. Ostriker and Paul J. Steinhardt in *Astrophysical Journal,* Vol. 530, No. 1, Part 1, pages 17–35; February 10, 2000; astro-ph/9901388

Dynamical Solution to the Problem of a Small Cosmological Constant and Late-Time Cosmic Acceleration. C. Armendáriz Picon, V. Mukhanov and Paul J. Steinhardt in *Physical Review Letters,* Vol. 85, No. 21, pages 4438–4441; November 20, 2000; astro-ph/0004314

Why Cosmologists Believe the Universe Is Accelerating. Michael S. Turner in *Type Ia Supernovae: Theory and Cosmology.* Edited by Jens C. Niemeyer and James W. Truran. Cambridge University Press, 2000; astro-ph/9904049