BRAVE NEW UNIVERSE

ILLUMINATING
THE
DARKEST SECRETS
OF THE
COSMOS

PAUL HALPERN AND PAUL WESSON

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Introduction:
The Quest for Cosmic Understanding

> *I am greatly relieved that the universe is finally explainable. I was beginning to think it was me. As it turns out, physics, like a grating relative, has all the answers.*
>
> Woody Allen (*The New Yorker*, July 28, 2003)

A short time ago cosmology seemed settled in the comfy chair of complacency, confident in the apparent resolution of many of its major issues. All known data converged on a uniform chronology of cosmic history—an account so widely accepted that it had come to be known as the standard model.

Every student of astronomy could recite the then-known facts: The universe began in a fiery explosion called the Big Bang and then expanded for billions of years. Over time its rate of expansion has gradually slowed and its constituent particles have come together to form galaxies, planets . . . and us. Eventually, depending on its material density, it will either fizzle out in a "Big Whimper" or shrink back down to an infinitesimal point in a "Big Crunch." These options were delineated by what are technically known as the Friedmann models: simple solutions discovered by Russian cosmologist Alexander Friedmann of the gravitational equations developed by Albert Einstein. The task of cosmology appeared relatively straightforward—to establish the precise age of the universe, firm up the sequence of events and reduce the possible endgames down to one.

Sure there were open questions, but mainstream cosmologists saw these as refinements. Most researchers believed in a clear-cut model of the universe that had little room for change after the first few moments of its history. Much debate was centered on pinning down what happened during the initial ticks of the cosmic clock.

A few of us pondered alternatives to the canon—theories of the universe that strayed from the simplest version of the Big Bang. Like the standard model, these were legitimate mathematical solutions—albeit of variations, reinterpretations, or extensions—of Einstein's equations. Mainstream cosmologists knew about such alternatives but tended to treat them as mere curiosities. In the absence of evidence to the contrary, these researchers advised, why reach beyond conventional approaches?

The situation was akin, in some ways, to the state of affairs before the age of Johannes Kepler and Galileo Galilei. From the 2nd century until the 16th century AD, astronomy relied on the coarse measurements of planetary motion recorded by the Alexandrian thinker Claudius Ptolemy (born circa 85 AD). In his pivotal text, the *Almagest*, Ptolemy developed a clockwork model of the solar system that corresponded well to his data. Consisting of wheels within wheels ultimately turning around Earth, Ptolemy's model showed how planets could follow distinct patterns as they moved across the sky. Because his scheme explained all known facts and fit in well with religious views, scholars found little reason to dispute it. True, it could be simplified, as the Polish astronomer Nicholas Copernicus pointed out, by placing the Sun at the center instead of Earth. But even Copernicus had no new data to back up his proposition.

What changed matters at the turn of the 17th century—as well as at the turn of the 21st century—were substantial improvements in astronomical measuring techniques that led to an enhanced understanding of the movements of celestial bodies. Superior naked-eye measurements of the Martian orbit taken by the Danish astronomer Tycho Brahe led Kepler to conclude in 1609 that the planets follow elliptical paths around the Sun. At approximately that time, images from the first astronomical telescope inspired Galileo to propose that the planets are worlds in their own right and that the stars are distant suns. These findings, in turn, led to the Newtonian portrait of a vast, possibly infinite, universe—home to myriad celestial objects interacting with one another according to the law of gravity.

Telescopes became larger and larger, revealing deeper layers of cosmic order. As they demonstrated, in the race across the celestial plains, stars are hardly lone rangers. Rather, they ride like horses on grand merry-go-rounds called galaxies. Galaxies belong to clusters—assembled, in turn, into even greater superclusters. In 1929, Edwin Hubble, using a colossal device on Mount Wilson in California, discovered that all distant galaxies are receding from each other. This finding led to the standard Big Bang model of an expanding universe—the crown jewel of 20th-century cosmology.

Just as it was enhanced observations that led science to abandon the Ptolemaic model and usher in the modern age, it is the dramatically improved equipment and techniques that have resulted in a rethinking of the standard cosmological approach. In the 1990s and early 2000s astronomy leapt above the clouds with extraordinary new orbiting instruments. Circling high above Earth at distances ranging from hundreds to hundreds of thousands of miles, these telescopic satellites have spanned the spectrum with their light-gathering power. Joining the Hubble Space Telescope, equipped to collect optical light, are infrared instruments, X-ray probes, and several microwave detectors—including the Cosmic Background Explorer and, most recently, the Wilkinson Microwave Anisotropy Probe (WMAP). WMAP has yielded the most precise estimate to date for the age of the universe: 13.7 billion years.

Space-based imaging has been accompanied by other astronomical breakthroughs. Digital cameras, able to absorb and record every single photon (particle of light) streaming down from space, have led to unprecedented precision and deeper-than-ever sky surveys. With these electronic spectacles, once-faint blurs have revealed themselves as extremely distant galaxies that can be analyzed and cataloged. Masterful computer algorithms piece together terabytes of photonic information into detailed three-dimensional images of space. Consequently, for the very first time, astronomy has added realistic depth to its spatial maps.

A leading ground-based project, called the Sloan Digital Sky Survey, has employed these state-of-the-art techniques in a comprehensive three-dimensional scan of a large portion of the northern sky. Mapping more than 200,000 galaxies, the survey has dramatically increased our knowledge of vast segments of space.

Paradoxically, though these instruments and programs have provided more information about the universe than ever before in scientific history, they have revealed how much we really do not know. In particular, they have confirmed a gnawing suspicion among cosmologists that the vast majority of the universe is composed of invisible materials and unidentified energies. As the telescopic results have indicated, only a small fraction of the mass of the cosmos constitutes ordinary matter. The rest is terra incognita! Not only do unseen powers appear to dominate space, they seem to govern its overall dynamics—causing the universe to expand at an ever-increasing rate. In short, we appear to live in an accelerating universe fueled by a hidden dynamo of mysterious origin.

This extraordinary discovery sent shock waves through the world of cosmology, displacing a number of long-held conceptions. No longer can cosmologists focus on the simplest models with the most basic kinds of matter—the textbook examples of expanding universes. Rather, the new findings have revealed more unusual possibilities and solutions.

Some of these novel proposals hypothesize strange new substances with properties unlike anything ever seen. Could, for instance, objects exist with negative mass? Could there be shadow worlds able to communicate with us only through the pull of gravity?

Could there be particles so energetic they have yet to be produced in our particle accelerators? Perhaps the next generation of powerful detectors will reveal such unusual entities.

Other revolutionary schemes involve modifying the law of gravity itself. Could it be that both Newton and Einstein—the greatest geniuses in physics—were wrong about the nature of the gravitational force? Perhaps their portraits of gravity, like unfinished masterpieces, require extra flourishes.

Yet another option involves transforming one or more of nature's constants into a variable. A group of physicists recently speculated that the speed of light could vary over time. Other "variable constant" ideas involve slowly changing values of the fine-structure constant (the parameter governing the strength of electromagnetic interactions), the gravitational constant, and even mass itself.

Finally, some of the most promising approaches for explaining the cosmological mysteries postulate the existence of a fifth dimension beyond ordinary space and time. The fifth dimension arises as a means of unifying all known forces of nature into a single theory. Although its origins date back to the early days of Einstein's general theory of relativity, it has recently been revived in methods for unification called supergravity, string theory, and M-theory.

Traditionally, if a fifth dimension exists, physicists have imagined it to be so small that it could hardly be detected. However, many contemporary approaches envision a large extra dimension, one comparable in scale to conventional space and time. In such a case the fifth dimension could influence the dynamics of the universe and possibly explain why it is accelerating. Moreover, if celestial mechanics is truly five dimensional, the Big Bang need not have been the beginning of time. Rather, it could have been a transition between different cosmic eras. Perhaps the actual cosmos is eternal and its finite age only an illusion wrought by the limitations of our senses.

Indeed, even with the best of all possible astronomical devices, much about the universe could well remain mysterious. Our place in the cosmos is incomparably small; our time in it is but a hummingbird's beat. It would not be too surprising if there are aspects of reality for which we, like dwellers on a tiny desert island, have little knowledge.

One of the greatest learning tools at our disposal is human intuition. Given our peripheral position in the oceans of space, we can use the power of logical deduction to infer much about what lies on distant shores. An outstanding example of the use of human intuition to extend our knowledge far beyond Earth involves the mystery of why the sky is dark at night. By applying some thought to this riddle, there is much we can learn about the universe at large.

1 To See the World in a Grain of Sand: What We Can Observe from Earth

> *To see the world in a grain of sand*
> *And heaven in a wildflower*
> *Hold infinity in the palm of your hand*
> *And eternity in an hour.*
> William Blake

IN THE DARK OF NIGHT

It is a familiar stillness—a lull in the rhythm of each day. As the Sun bursts into spectacle and recedes from the sky, ever-darkening shades of color mark its descent. Once the principal player exits the stage, the deep blue backdrop gradually fades into black. Soon no trace of light can be seen, save perhaps the soft glow of the Moon and the pinpoint patterns of the stars and planets.

Most of us take the darkness of the night sky for granted. Yet if one gives it some thought, the blackened nocturnal visage that inspires serenity and sleepiness ought to be a flood-lit, insomnia-inducing glare. Given the vast energies of the universe, pouring radiation ceaselessly down on Earth, we should not need street lamps to navigate nor indoor lighting to read. Evening sporting events ought to be as vivid as day games, midnight strolls as bright as noontime walks.

Think about all the luminous energy constantly bathing our planet. Space contains billions of galaxies, spread out uniformly through the sky. Journeying in any direction, the farther out you go, the more galaxies you'd encounter—passing one after another like mile markers on a Nebraska highway. And a typical galaxy pumps out light at a colossal rate. All these sources of illumination, added up, should be enough to rival sunlight and put an end to the dimness when the Sun isn't even in view. Then why is endless space and, therefore, the night sky not ablaze with light?

The dark sky riddle slipped into astronomical folklore thanks to Heinrich Wilhelm Olbers, a German physician and amateur astronomer. In 1826 he argued that in a uniform, infinite universe populated by eternal and unchanging stars we could potentially see an arbitrarily large number of them. The farther away we looked, the more and more we'd see, because the number would increase as the cube of the distance.

This cubic relationship is like baking larger and larger blueberry muffins. While a thimble-sized pastry might be large enough to contain one blueberry, double each of its dimensions, and it might easily accommodate eight. Make it 10 times bigger in diameter and height and it might even pack in a thousand such morsels. Imagine all the juice that would leak out if all of these were to burst while baking. Similarly, picture all the light produced by greater and greater scopes of stars, each shining in all directions. The amount of illumination heading toward us would be tremendous.

Given a vast-enough cosmos, every single point on the sky should glow with the light of a brilliant star. Bombarded with the colossal radiation of myriad luminous objects, we should need to wear sunglasses night and day. The fact that this does not happen and that the nocturnal sky looks dark has become known as Olbers' paradox.

Scientists wrestled for more than a century and a quarter with this dilemma before beginning to zero in on two conceivable solutions. One possibility, promoted in the 1950s and 1960s by astronomer Hermann Bondi and others, concerns the role of the expansion of the universe in diluting light. Discovered by Edwin Hubble in the 1920s, this expansion reveals itself in the recession (outward movement) of remote galaxies, relative to our galaxy, the Milky Way. Hubble found that the farther away a galaxy, the faster it appeared to be moving away from us. Noting this universal relationship, known as Hubble's law, Bondi argued that the light from distant bodies would become weaker and less energetic the farther it has to travel toward Earth. This effect would greatly dilute the amount of radiation that reaches us, thereby enabling darkness at night.

Considering its critical scientific importance, it was natural for scientists to bring Hubble's law into the discussion. Hubble's revelation of the universal expansion of space is one of the greatest astronomical discoveries of all time. He discovered this effect through a careful study of the atomic spectral lines found in galactic light.

Spectral lines are the fingerprints of atoms, uniquely characterizing their internal structures. As quantum physics tells us, each type of atom has a particular arrangement of energy levels that its electrons can occupy. Like workers ascending or descending a ladder, stepping up and down on certain rungs, electrons are restricted to specific energy states. Each time an electron drops from a higher to a lower level it emits a photon that carries away that energy difference. On the other hand, whenever an electron rises from a lower to a higher level, it must absorb a photon that infuses the required amount of energy. Quantum physics further informs us that photons have wavelike characteristics, vibrating at various rates depending on their energies. The more energetic a photon, the greater its frequency (rate of vibration). Therefore, the energy profile of an atom translates into a unique arrangement of frequencies of the light emitted or absorbed. Physicists refer to these, respectively, as the emission and absorption spectra.

A well-known property of waves, known as the Doppler effect, is that their observed frequencies shift with the speed of the source. A wave moving away from an observer takes on an extra time lag, which makes it appear to vibrate slower. Conversely, a wave moving closer saves time due to its forward motion and seems to vibrate quicker. In the former case its frequency shifts downward, and in the latter case its frequency shifts upward.

Imagine a steady letter writer, traveling around the world, who mails a postcard to a close friend every single day. If she is traveling away from her friend, to lands increasingly remote, her postcards would likely take longer and longer to arrive. Thus, the frequency by which her friend would receive them would steadily drop. On the other hand, if she is making her way back home, her friend's letter box would likely fill up at an increasing pace. Letters sent weeks before from faraway lands might arrive at the same time as those sent days before from nearer locales, leading to a glut of mail. Similarly, as the Doppler effect informs us, the direction of a signal's sender affects its frequency upon arrival.

For sound waves the Doppler effect explains the high-pitched shrieking of a fire engine as it races toward a scene and the low-pitched moan as it speeds away. In the case of light waves, the Doppler effect is visual. Applied to the inward or outward motion of a source, it predicts a shift in luminous frequencies toward the higher or lower ends of the spectrum, respectively. In terms of colors, blue has a relatively high frequency and red a low frequency. Therefore, the increase in frequency for approaching sources (from green to blue, for example) is known as a "blueshift," and the decrease of frequency for receding sources (from orange to red, for instance) is called a "redshift."

Hubble pioneered the use of this effect to probe galactic motions. Pointing the Hooker Telescope (at that time the largest in the world) at various galaxies, he recorded shifts in the frequencies of their atomic spectral lines. He used this information to calculate the velocities (either incoming or outgoing) of each galaxy relative to Earth. Plotting these with respect to galactic distances, he discovered, to his amazement, an unmistakable pattern. With the notable exception of our nearest neighbors (such as Andromeda), all other galaxies in space emit redshifted light—and are therefore racing away from us, like engines from a firehouse. As Hubble observed, the more distant the galaxy, the faster its recessional speed.

The Milky Way isn't alone in being shunned by remote galaxies. We occupy no special place in the cosmos and must assume that the behavior of the galaxies in our region is essentially the same as galaxies everywhere. Therefore, all the distant galaxies must be moving away from each other as well, pointing to a grand expansion of space itself.

Note that the universal expansion does not cause Earth itself to grow bigger. Nor does it cause the solar system to enlarge. Rather, it operates solely on the grandest level: the arena of the Milky Way and its many galactic cousins. Their colossal feud has little effect on our planet—except for telltale signs in the light that the distant galaxies produce. As physicist Richard Price of the University of Texas at Brownsville recently said, "Your waistline may be spreading, but you can't blame it on the expansion of the universe."

The Hubble expansion includes two effects that bear on Olbers' paradox and they concern the energy and density of radiation. The redshifting of light causes it to lose energy. Red starlight, for example, is cooler than yellow. Consequently, as the universe grows, its radiation becomes less powerful. Furthermore, the enlargement of space offers ever-increasing room for photons (light particles). As time goes on, each cubic foot contains, on average, fewer and fewer of these particles. Thus, the Hubble expansion has a double-barreled effect: It cools and dilutes the light in the universe. It makes Earth's night sky darker than it would have been otherwise. Therefore, according to this explanation, the reason we aren't immersed in light is similar to someone trying to take a hot bath in an ever-expanding bathtub. The growth of the bathtub would continuously cool the water and lower its level. Over time, nothing would remain but cold, isolated droplets. By analogy, Earth's night sky displays cooled-down, scattered points of light rather than a warm, luminous flood.

This is an elegant explanation, no doubt. But is it the truth? Sometimes nature baffles us with competing ways of explaining the same effect. The extinction of the dinosaurs, the origin of life, the birth of consciousness, and many other scientific quandaries have triggered formidable debate—with vying accounts struggling for prominence over the years. In this case, science has offered an alternative resolution of Olbers' paradox—one that is different from the Hubble expansion.

POE'S EUREKA MOMENT

Curiously, the true solution to Olbers' paradox has a long literary history. In 1848, Edgar Allen Poe published *Eureka: A Prose Poem*, a volume of his assorted musings about the universe. Recognizing the dilemma of nocturnal darkness, Poe suggested resolution by assuming that light from only a *finite* set of stars has reached us. As Poe wrote:

> Were the succession of stars endless, then the background of the sky would present us a uniform luminosity, like that displayed by the Galaxy—since there could be absolutely no point, in all that background, at which would not exist a star. The only mode, therefore, in which, under such a state of affairs, we could comprehend the *voids* which our telescopes find in innumerable directions, would be by supposing the distance of the invisible background so immense that no ray from it has yet been able to reach us at all.

In other words, Poe divided the universe into two categories. The first part—only a minute fraction—are the stars close enough for their light to have already reached us. The second region—the majority, by far—consists of unimaginably distant objects emitting rays that have yet to touch Earth's skies.

If the universe were infinitely old, Poe's argument wouldn't hold water. No matter how remote a luminous object, we'd witness its light given off some time in its past. For example, if it were billions of light-years away, we'd see its light rays emitted billions of years ago. If it were trillions of light-years away, we'd view its multi-trillion-year-old illumination. This follows from the definition of a light-year: the distance light travels in one year (about 6 trillion miles).

Poe believed and modern science has confirmed, however, that the universe has a finite age. According to current understanding, about 13.7 billion years ago the entirety of space emerged from nothingness (or a prior form) in a mammoth outpouring of energy known as the Big Bang. This material coalesced into whirling galaxies that, in turn, provided the nurseries for myriad stars. Thus, because children cannot be older than their parents, no star has been emitting light for longer than the age of the cosmos. Most stars—the Sun being a good example—are in fact much younger.

A key prediction of the Big Bang theory was confirmed in 1965 through the detection of radiation left over from its initial stages. The relative uniformity of this relic radiation indicated that it had a common source—namely, the explosive beginning of the universe. Thus, the direct cause of the Hubble expansion was the emergence of the cosmos from a fireball.

The same year as the Big Bang's verification, University of Massachusetts astronomer Edward Harrison made use of this finding to spin a modern version of Poe's tale. Because all the stars and galaxies have finite ages, he noted, there has not been enough time for space to flood with their light. Therefore, when we gaze at the night sky we see only the illumination of objects that are close enough and old enough for their light to have reached us. This illumination represents only a small amount of light, leaving the rest of the heavens as black as the depths of a cave.

This situation can be compared to the maximum range of signals from television stations on Earth. One of the first experimental broadcasts took place in the late 1920s, transmitting an image of the cartoon character Felix the Cat. Traveling at the speed of light, by now Felix's visage has spread out across a spherical region of space almost 80 light-years in radius, encompassing hundreds of stars. Any intelligent beings residing within that shell, capable of interpreting our signals, would know that we have television (and would conceivably become acquainted with Felix). Yet because television is relatively new, the vast bulk of the universe has yet to encounter our broadcasts. Thus, the fraction of the cosmos containing our television signals is virtually nil. Similarly, because of the finite age of stellar "broadcasts," the intensity of local starlight is extremely small.

For several decades, both explanations for Olbers' paradox appeared in various texts. At one point—by our estimate—about 20 percent of the books said the night sky is dark because the galaxies are receding from each other, while another 30 percent said the reason lies in their finite age. The rest mentioned both factors but did not say which is more important. The lack of a clear answer to such a fundamental question seemed a scandal of the first order.

In the mid-1980s, one of us (Wesson) along with two colleagues, Knut Valle and Rolf Stabell of the University of Oslo, set out to nail down this matter in a way the entire astronomical community would accept. A series of fruitful discussions led to the definitive resolution of the problem. The results were published in the June 15, 1987, issue of the *Astrophysical Journal,* the leading journal in its field.

To construct its solution, the team conducted a clever thought experiment. In its alternative version of cosmic reality, it pictured preventing the expansion of the universe while keeping all other properties of the galaxies (particularly their ages) the same. In this manner the group ascertained the intensity (brightness) of intergalactic light in a static universe, implying that the finite age of the galaxies was the determining factor. Then it allowed the expansion to resume, knowing that both the age factor and the expansion factor controlled the intensity of intergalactic light. Finally, it found the ratio of these intensities, establishing the relative importance of each factor.

The group's experiment was like observing a city scene during moonless and moonlit nights to see whether moonlight or street lamps contributed more to urban illumination. By varying one feature while maintaining the others, it was straightforward to compare their effects. The results were undeniable, setting aside years of controversy. The team estimated the typical ratio of intergalactic light with expansion to be only about one-half of that without it. Given the flood of energy produced by all the galaxies, the expansion of the universe thereby made little difference. Rather, the age factor produced by far the greatest impact, robbing the heavens of the vast majority of its potential brightness. Hence, even in a static universe, the sky would be plenty dark.

This experiment resolved Olbers' paradox once and for all: The night sky is dark because the universe is still young, not because it is expanding. So the next time you stub your toe in the dark of night, you can justifiably blame it on the Big Bang.

Where Are the Aliens?

Not only is space black, it is also silent. Surrounded by endless stellar reaches, Earth seems a lonely outpost devoid of communications from any other world. Given the likelihood of planetary systems orbiting many (if not most) of the stars we see, why hasn't a single one of them sent us a simple hello? Could space be as empty of life as it is of light, or might there be another explanation?

The great Italian physicist Enrico Fermi pondered this dilemma in 1950 while taking a break from the rigors of Los Alamos Laboratory. It was the era of the UFO craze, and newspapers were brimming with speculations about the prospects for alien visitors. A clever cartoon about the subject caught his eye and led him to estimate the probability of extraterrestrial contact. During a casual lunch, he raised the topic with three of his colleagues—Edward Teller, Herbert York, and Emil Konopinski. While discussing sundry matters, Fermi suddenly asked, "Where is everybody?"

Fermi's lunchtime companions knew him as a man of deep thought and did not take his question lightly. As an expert in seat-of-the-pants calculations, he was adept at ruling in or out various physical scenarios. If the esteemed planner of the first self-sustained nuclear reaction was troubled by a missing element, chances were that something was wrong.

The “everybody” in question referred to the preponderance of extraterrestrials our vast universe ought to contain. As Fermi pointed out, given a sufficient number of worlds in space, at least a fraction of them should harbor civilizations advanced enough to attempt contact with us. Then, considering that the cosmos has been around for billions of years, why haven’t any of them sent signals by now? The curious situation that Earth has never encountered alien communications has come to be known as Fermi’s paradox.

Belief in the abundance of life in the universe dates at least as far back as the early days of the scientific revolution. Many notable thinkers have stressed that if life emerged from Earth’s once-barren soil, it ought to have arisen on countless other planets as well. Isaac Newton, for example, once wrote, “If all places to which we have access are filled with living creatures, why should all these immense spaces of the heavens above the clouds be incapable of inhabitants?”

Ten years after Fermi’s remark, astronomer Frank Drake developed an equation that has come to epitomize the chances of encountering intelligent life in the universe. The Drake equation consists of a number of multiplicative factors, each of which represents one aspect of the likelihood for alien contact. These factors include $N*$, the number of stars in the Milky Way; f_p, the fraction of stars that have planetary systems; n_e, the average number of planets in each system that have environmental conditions suitable for life; and f_l, the chances that life actually arises. The final three parameters pertain to the emergence of intelligence itself: f_i, the fraction of life-nurturing worlds with intelligent beings; f_c, the fraction of those with cultures advanced enough to broadcast messages; and f_L, the longevity of such civilizations. Except for $N*$ and n_e, each of these factors ranges from 0 to 1 (with 0 representing “none” and 1 representing “all”). The product of all these factors yields an estimate of

N, the number of civilizations in our galaxy potentially able to contact us. In equation form, Drake wrote this as:

$$N = N* f_p n_e f_l f_i f_c f_L$$

Some of these factors are more quantifiable than others. For example, models of stellar and planetary formation are fairly well developed. Although at the time Drake proposed his equation scientists knew of no other planetary systems, in recent years they have discovered more than 100 worlds beyond the solar system. As a consequence of these findings, researchers have developed superior estimates for the fraction of stars with planetary companions. Astronomer Geoff Marcy, one of the leading planet hunters, has recently surmised that roughly half of all stars have planetary systems.

Scientists have been far more tentative about the prospects for life and intelligence on other worlds. Because no living organisms have been found yet in space, let alone cognizant beings, the components of the Drake equation pertaining to these possibilities are still highly speculative. Nevertheless, Drake and other astronomers have offered guesses as to their ranges. Carl Sagan, for example, argued that the number of advanced civilizations capable of communicating with us could be as low as 10 or as high as in the millions, depending on their capacity to avoid nuclear destruction.

Drake and Sagan were leading proponents of the Search for Extraterrestrial Intelligence (SETI), a systematic hunt for radio signals from alien civilizations. Beginning in the 1960s, radio dishes around the world have scanned the skies for telltale coded patterns. In the intervening decades the SETI program has been greatly expanded, encompassing a wider range of frequencies and a broader array of targets. Improved software and faster processing rates have made it easier to wade through the haystack of radio noise, thereby enhancing the prospects for uncovering buried messages. Alas, despite a number of false alarms, not one has been found.

In the 1970s, baffled by the constant lack of evidence for extraterrestrial civilizations, a number of scientists put forth proposals suggesting that advanced life in the cosmos (or at least our galaxy) is extremely rare. The most famous of these proposals was a paper by astronomer Michael Hart, advancing the startling proposition that we are the first civilization in the Milky Way. Hart reached this conclusion through a systematic study of conditions that could realistically affect alien communication, none of which would present enough of an obstacle to persistent aliens who wanted to contact us. If extraterrestrials that were currently capable of radio transmissions existed, we surely would have heard from them by now. Thus, Hart answered Fermi's famous question with the discouraging solution that nobody able to talk to us is around yet.

Tulane physicist Frank Tipler amplified Hart's suggestion with a detailed explanation for ruling out the existence of intelligent extraterrestrials beyond Earth. Tipler argued that any extant advanced civilization would have at some point in its history developed the means for galactic colonization through an army of self-reproducing robot ships. These automata would be programmed to explore new worlds, establish outposts on the most suitable ones, and then fashion replicas of themselves to repeat the process elsewhere. By now, Tipler contended, the Milky Way would be replete with signs of one or more such civilizations. The absence of such signs led Tipler to conclude that the only intelligent beings in our galaxy were his fellow humans.

BEYOND THE COSMIC HORIZON

Even if advanced life is rare in the Milky Way, that does not preclude an abundance of civilizations in other galaxies. An infinite universe would render even the slimmest chance for intelligence a reality *somewhere* else in space. Given enough room in the cosmos and enough time for intelligence to develop, the cosmic roulette wheel would be bound to hit the lucky number. It would be just like placing a million monkeys in front of a million computers and letting them bang on the keyboards for an extremely long time. Eventually, through their random actions, one of them would type a Shakespearian sonnet.

The lower the probability for intelligent life to evolve, the farther we need to look to find it. Hence, before drawing conclusions about the current failure of the SETI mission to discern signals from within the Milky Way, we must expand our search to include other galaxies. Although the present-day program envisions civilizations with the capacity to broadcast messages over tens or hundreds of light-years, we can easily imagine extragalactic cultures with even greater capabilities. Moreover, because each galaxy potentially harbors hundreds of billions of worlds, there could very well be far more civilizations able to reach us with their signals outside the Milky Way than within it. Therefore, by aiming our radio dishes at intergalactic as well as intragalactic targets we might improve our search for extraterrestrial intelligence.

Suppose comprehensive scans of the heavens—including the broadest possible scope of galaxies—continue to fail to turn up signs of sentient life. Should the science community then conclude, like Tipler, that we are alone in the cosmos? Or could there be another reasonable explanation for the complete lack of communication?

To address this issue, let's draw a valuable lesson from the way we resolved Olbers' paradox. In that case we found that the finite age of galaxies and the finite speed of light conspire to shield us from the totality of radiation emitted in space, letting only a minute portion reach our skies. Similarly, perhaps the finite age of extraterrestrial civilizations and the finite speed of light preclude us from receiving alien broadcasts. In contrast to starlight and galactic light, maybe the effect is so severe that not even a single message would be able to reach us.

If that seems odd, think about the case of the Felix the Cat signals broadcast in the 1920s. Because of the limitations posed by the speed of light, only a small fraction of the stars in the galaxy are close enough (within 80 light-years) to have already come into contact with those signals. Suppose intelligent life is rare enough that none of these nearby stars have planets inhabited by civilizations capable of radio communication. Then presently no other world in space could possibly know about Felix and his human creators.

If we now imagine intelligent life so uncommon that the nearest communicative civilizations lie in remote galaxies, we can see how vast distances could preclude contact. A culture millions or billions of light-years away would have had to be broadcasting for eons in order for us to know about them. If we use the history of life on Earth as the model, many planets would have been too primitive to support advanced beings that long ago. Therefore, no communicative civilization would be ancient enough for its signals to have already reached us.

Moreover, on galactic scales the expansion of the universe would greatly exacerbate the time delay. Because the alien races would be situated in galaxies fleeing from ours, their radio broadcasts would need to cross ever-widening gulfs. Hindered by the currents of outward galactic movement, any messages sent out would wash up on our shores far, far later than they otherwise would in a static universe.

If the closest civilizations are even farther away, we would never learn of their existence. As cosmology tells us, beyond an invisible barrier called the *particle horizon*—defined as the greatest distance any incoming particle could have traversed in the universe's current age—alien signals wouldn't stand a chance of reaching us. They'd face the situation of Alice in the looking-glass world; though they'd travel as fast as they could, they wouldn't be able to outrace the expansion of the universe.

Indeed, it's entirely possible that a cornucopia of worlds could reside beyond the curtain of invisibility. Some of these planets might even be Earth's near twin. Others could house technologies exceeding our wildest speculations. Yet unless any of these societies find a way of circumventing the speed of light, we would remain as separate from them as prisoners confined forever to solitary cells.

From our resolutions of the paradoxes posed by Olbers and Fermi we have seen that there really isn't just one universe. The *observable* universe—consisting of all the galaxies within communication range—comprises but a fraction of the entire physical universe. Features of the former, including the relatively sparse nighttime sky and the lack of evidence for extraterrestrial signals, do not necessarily reflect the complete cosmos. We could well be living in an infinite space with unlimited sources of energy and myriad worlds wholly beyond our perception.

The Frontiers of Knowledge

An integral part of the human condition is that we are faced with limits. Our senses and abilities can take us only so far. Beyond them lie vast stretches of unknown territory. None of us have been to the surface of Pluto or to the bottom of the Marianas trench. No one has ventured into the center of the Earth or traveled backward through time. Confined through mortality to just a tiny sliver of eternity, we will never experience the distant past or the far future. Yet we are a race of dreamers and cannot help but ponder the wonders that might reside in places beyond our reach.

Our intellect yearns for knowledge of the cosmos in its entirety. Therefore, it is frustrating to think that much, if not the bulk, of the physical universe lies outside our range of observation. It is even more unnerving to realize, as recent evidence has shown, that the conventional material we *do* detect is far outweighed by invisible material. Atoms and molecules—the stuff of planets and stars—are but minority occupants of space. The major players are bizarre entities known as dark matter and dark energy. Until we fathom these substances, we have taken only a child's step toward comprehending the universe as a whole.

Dark matter was originally postulated as an explanation for unexpected discrepancies between the actual and predicted motions of certain celestial bodies. In the early 1930s, Dutch astronomer Jan Oort noticed that the stars in the Milky Way tend to be drawn much more tightly to its central plane than Newton's law of gravitation would require. Estimating the theoretical value of the collective pull of our galaxy on each of its stars, Oort found that the observed amount is three times greater than expected. It is like a ghostly tug-of-war with powerful apparitions assisting each live player.

Shortly thereafter, Swiss physicist Fritz Zwicky discovered a related effect concerning the behavior of galaxies in clusters. A cluster is a stable collection of galaxies, held together through the force of gravity. Examining the Coma Cluster (in the constellation Coma Berenices), Zwicky calculated the amount of matter needed to provide its gravitational "glue." To his astonishment, he found that the required mass is hundreds of times what astronomers observe telescopically. (He had made an error in his assumptions, but even with the correction there was a significant discrepancy.) Zwicky postulated that the bulk of the material in the Coma Cluster is invisible.

It wasn't until the late 20th century, however, that the mainstream scientific community reached the unmistakable conclusion that there is far more to the cosmos than meets the eye. Astronomical sleuthing, gleaning results from a phenomenon known as gravitational lensing, demonstrated that dark matter pervades the universe—from the hearts of galaxies to the voids of deepest space. This method measures the bending of light from distant objects due to the gravitational influence of intervening bodies—seen or unseen. It relies on a concept proposed by Einstein in his general theory of relativity—massive objects warp the fabric of space and time, causing photons and other particles to alter their paths. Thus, the weighty presence of matter—even invisible material—can bend light like a lens. Astronomers can determine the amount of distortion in a section of space by observing changes in the apparent brightness or position of the light sources passing behind it—like watching bugs alter in appearance as they crawl beneath a magnifying glass. Then these observers can calculate how much mass must have caused the curving. Offering an extraordinary tool for mapping out the hidden material in the cosmos, gravitational lensing has furnished ample evidence that luminous bodies comprise just a small subset of all that there is.

What is this mysterious substance that signs its name only with gravity's mark? Early on, scientists supposed that it was nonshining stars, meaning those that either burned out or never had enough material to ignite in the first place. Examples of these would be objects called neutron stars (the ultracompact remnants of massive stellar cores) and brown dwarfs (stars comparable in size to very large planets, lacking the critical mass of hydrogen required to stoke the furnace of stellar fusion). Further measurements, though, have indicated that nonshining stars represent only a portion of the missing material. Most of the hidden stuff must be composed of new kinds of substances—rather than the ordinary matter, made of protons and neutrons, that constitutes stars and planets.

Cosmologist Michael Turner of the University of Chicago has offered a number of suggestions for what dark matter could be. At scientific conferences he lays out his ideas on colorful transparencies, wagering like a sports commentator which are the best bets. His prime candidate is a hypothetical particle called the axion, to which he gives high odds despite the fact that powerful detectors have searched for it in vain.

To further complicate matters, in 1998 an extraordinary astronomical discovery seemed to cast even more of the cosmos into shadow. Using precise measurements of the distances and velocities of supernovas (stellar explosions) in extremely remote galaxies, several teams of astronomers determined how the Hubble expansion changes over time. To their amazement, they found that the universe's growth is speeding up as it ages. Not only is the cosmos ballooning outward, it is doing so faster and faster—with no end in sight.

Until the supernova findings, many astronomers assumed that the long-term evolution of space would constitute one of two possibilities depending on the amount of mass within it: either continuing to expand forever at a slower and slower pace, slowed by the mutual gravitational attraction of all its matter and energy, or, if its density exceeds a certain critical amount, reversing course and recontracting down to a crunch. The options resembled a roller coaster nearing the end of its track. Virtually everyone expected a gradual slowdown, followed perhaps by a backward ride. Few thought the vehicle would be charging full speed ahead.

Ordinary gravity cannot account for such acceleration. As an attractive force, it acts to clump massive objects together, putting brakes on the outward motion of the galaxies. Because both dark and visible forms of matter interact on the basis of gravitation, they could not engender the repulsive forces required to push galaxies apart. Turner and other researchers rapidly reached the conclusion that a new type of substance must be at work, one that creates a kind of cosmological antigravity. They dubbed the unknown agent “dark energy” to distinguish it from dark matter.

There are several important differences between dark matter and dark energy. While dark matter is thought to have an uneven distribution, mainly clumped around visible population centers (with a lesser amount sprinkled throughout the void), dark energy is believed to be as smooth as custard, spread uniformly throughout space. Otherwise, in contrast to known observations, the universal expansion would exhibit distinct behavior in various directions.

Moreover, although the composition of dark matter is largely unknown, scientists have put forth an array of likely candidates. Any massive, but elusive, particle present in sufficient quantities could potentially fit the bill. A prime example is the neutrino, a fast-moving particle believed to comprise at least a portion of dark matter.

By comparison, dark energy contenders have been much harder to identify. Proposed explanations have called on entirely new physical paradigms, stretching the limits of our imagination. Some of the suggestions include introducing an altogether novel type of energy field called quintessence or even modifying the law of gravity itself.

Recent results from probes of the cosmic microwave background have pinned down the relative abundance of dark matter and dark energy on the one hand, compared to luminous materials on the other. According to the WMAP survey, considered the most precise scan of cosmic background radiation ever conducted, about 23 percent of the mass of the observable universe is composed of dark matter, about 73 percent is dark energy, and only 4 percent is ordinary visible material.

Presented with such startling evidence of our minority status in a vast and dark cosmos, scientists can no longer assert that their celestial charts reflect the true picture of reality. These findings have presented cosmology with one of its greatest challenges in history: shedding light on the shadowy substances that dominate the physical world.

Calling on Einstein

Intuition took us far in pondering solutions for Olbers' paradox and the Fermi paradox. By pressing forth the ramifications of several basic principles—the finiteness of the speed of light, the limited age of the universe, and the Hubble expansion of space—we found ways to explain nocturnal darkness and the lack of alien communication in the face of a possibly infinite universe. Keeping these successes in mind, let's apply scientific reasoning to cosmology's greatest enigmas—including the puzzles of dark matter and dark energy.

One of the great champions of thought experiments, Albert Einstein, developed a remarkable equation that will aid us in our pursuit. It is not his most famous equation, linking energy and mass, but rather a relationship between the matter and geometry of any region of space. The basis of his general theory of relativity, it demonstrates how matter affects the universe itself. Not only does it predict the Hubble expansion, it also yields precise forecasts for what happens if the mixture of dark matter, visible matter, and energy is altered. Moreover, it even includes an antigravity term, called the cosmological constant, that can be interpreted as representing the impact of dark energy on universal dynamics.

The route Einstein took to his grand equation was extraordinary. Putting forth bold insights about gravitation, accelerated motion, and the roles of space and time, he crafted this raw material through the machinery of mathematics into a beautiful edifice unmatched for its elegance and simplicity. Showing little wear for its age—at least until recently—this construction has provided sturdy support for the burgeoning field of cosmology.

Although one is loathe to tamper with success, it could be that Einstein's construct will require reinterpretation or even modification to bear the added weight of contemporary astrophysics. Before considering such options, however, let us retrace Einstein's steps and examine how he assembled various physical suppositions into a masterpiece of mathematical architecture.