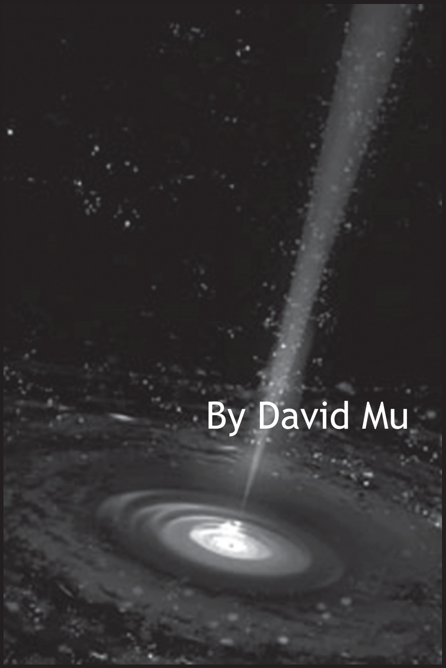
Quantum Black Holes, Unseen Dimensions

The World Stuck to a Brane



By David Mu

credit: NASA, http://maxim.gsfc.nasa.gov

The world is not as it seems. Fifteen hundred years ago, people believed that the earth was flat. Five hundred years ago, we were convinced of the truth of spontaneous generation, in which life sprung inexplicably from inanimate objects. And up until one hundred years ago, we were certain that space and time were absolute. The scientific discoveries that helped debunk these old-world views effected nothing less than paradigm shifts in our understanding of the natural world. They challenged and prevailed over deeply ingrained beliefs concerning the most fundamental questions of life and the makeup of the physical universe. Now, at the dawn of the new millennium, we may yet again be at the brink of another such shift in knowledge. Research at the frontier of theoretical and experimental physics has converged to weave an enchanting tale entangling such exotic entities as quantum black holes, hidden dimensions, and sticky membranes. This tale, if verified by experiments soon to be taking place, will undoubtedly challenge our very conception of space, and open up an entirely new frontier in physics research. The world may still not be what it seems.

Black Holes Big and Small

To better understand the questions being investigated at the front lines of this research, we begin by examining a familiar object that has long pushed the boundaries of human understanding: the black hole. Comprised of an extremely concentrated mass in a small volume of space, a black hole is a region of space-time in which the gravitational field surrounding it is so strong that nothing, not even electromagnetic radiation such as visible light, can escape its pull (1). Interestingly, while we generally associate black holes with the remnants of massive stars, it has long been hypothesized that smaller black holes could have formed in the early universe when the average density of matter was much greater (2). During these earlier periods of cosmic expansion, "primordial" black holes could have collapsed out from irregular patches of high-density space. They would have been small compared to their better-known black hole cousins, with a mass similar to that of a mountain, but squeezed into the size of an atomic nucleus (3)!

This seemingly paradoxical idea of black holes existing not on the macroscopic, but on the microscopic scale prompted investigations into possible quantum effects that might govern black hole behavior. In the mid-1970s, the eminent astrophysicist, Stephen Hawking published his landmark finding that black holes not only engulf matter, but emit it as well (4). This emission, now referred to as Hawking radiation, carries off energy from the black hole and effectively reduces the size of the black hole over time. Furthermore, the rate of emission is inversely proportional to size, so that the smaller the black hole becomes, the faster it emits radiation. As a result, while all black holes evaporate over time, the evaporation of small primordial black holes occurs at a much faster rate.

The vaporization of black holes, as mediated by Hawking radiation, raises an intriguing question: what happens to the information that falls into a black hole? If black holes completely evaporate, as Hawking suggested, then information that fell into the black hole would be lost forever—a direct violation of the principles of quantum mechanics and conservation of energy. While Hawking has recently come around and admitted that black holes perhaps do not completely destroy the information that falls into them (5)—an admission that cost him a baseball encyclopedia by way of a lost wager—the laws governing the behavior of black holes are still not fully understood. While much valiant theoretical work has been done to mathematically model black holes, and, more recently, quantum black holes (6), their exact nature remains elusive.

Black Hole Factories

One possible approach to gaining a better understanding of black holes—especially of the extremely small variety—is through direct observation. Recently, a group of scientists made the controversial claim that primordial black holes are ubiquitous objects in the universe and that their existence can be detected through short wave gamma-ray bursts (7). While the reported findings are still hotly debated, the possibility that primordial black holes could leave behind detectable footprints as they evaporate is highly intriguing.

A different, and perhaps even more exciting approach to studying black holes involves their artificial production in high-tech laboratories. As a black hole is nothing more than a large amount of mass squeezed into a very tight volume of space, in theory a person could create a miniature black hole in the palm of his hand if he had the requisite muscle strength (8). Obviously, no person is strong enough to provide this amount of power, but it may be possible in the near future for particle accelerators to smash heavy particles together with just the right amount of force necessary to generate a small black hole.

A strong candidate for running such an experiment is the Large Hadron Collider, or LHC, which is located at the European research institute, CERN. A circular particle accelerator capable of smashing together two beams of protons traveling at 99.999999% the speed of light (9), the LHC can impart up to 7 teraelectron volts (TeV) of energy to a single proton in accordance with Einstein's famous equation, $E= mc^2$. (An electron volt is the amount of energy needed to move an electron across an electrical potential difference of 1 Volt.) To get a better feel for energy at this scale, by comparison, a flying mosquito has an energy of about 1 TeV (9). Hence, a single accelerated proton in the LHC would have the energy equivalent of 7 flying mosquitoes!

> *"If we are fortunate enough to detect the creation and the almost instantaneous evaporation of quantum black holes, we could be almost certain of the existence of hidden dimensions."*

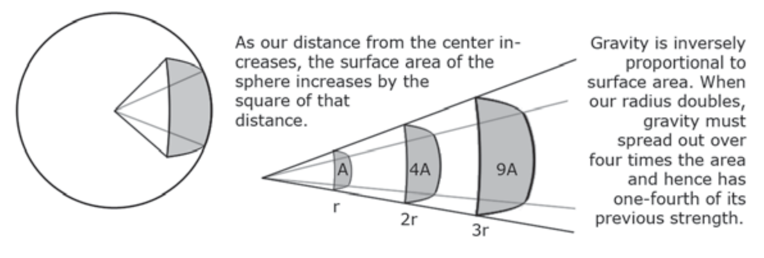
The prospect of accelerating protons to near the speed of light only to smash them to smithereens is, if nothing else, amusing. The real question, however, is whether these experiments are of any true scientific value. It should please the reader to know that smashing together protons inside huge particle accelerators with the hope of generating black holes is not simply a fun exercise to gratify the inquisitive mind. On the contrary, the results of such particle acceleration experiments hold profound consequences for our understanding of the very fabric of space. As we will soon see, the generation of quantum black holes can reveal very counterintuitive features of the world in which we live.

The Unseen Dimensions

Set to become operational at the beginning of 2007, the LHC is a remarkable piece of machinery. With a circumference of 27 km and buried in a tunnel 100 meters below the Swiss-French border near Geneva, the LHC by far outstrips any other particle accelerator in power (10). Yet according to conventional physics theory, even protons colliding with an energy of 7 TeV may not be energetic enough to create a black hole (2). Because particles such as protons also behave like waves, there is a lower limit to the volume of space into which they can be compressed. As a result, even when two protons collide while traveling near the speed of light, at the collision interface, the mass density may still not reach the threshold density necessary for black holes to form.

Is the prospect of creating quantum black holes in the laboratory therefore just a far-fetched dream? The answer may be quite revealing. The calculations of the critical density and critical energy values needed for black hole generation are based on classical theories of gravity in which the gravitational force varies inversely with the square of the separation distance between two objects. While this inverse square law models our macroscopic universe—from planetary motion to falling objects— extremely well, it has only been verified for scale lengths greater than about one tenth of a millimeter (11). Indeed, as is postulated by string theory, the only self-consistent theory we have of quantum gravity, space-time may actually be comprised of many small spatial dimensions in addition to the familiar three (12). If this is true, then the force of gravity may actually be a lot stronger at close distances than previously suspected.

To better understand why this would be true, let us take a closer look at the nature of the gravitational force. We can represent the gravitational field of an object by drawing gravitational field lines emanating from the object's center (Figure 1). We can think of the strength of the gravitational field at any point as proportional to the density of the field lines—that is, the closer the field lines are drawn together, the greater the gravitational force is. In a three-dimensional world, the gravitational field lines would be spread out over a spherical shell of radius r at a distance r from the object. Hence, the force of gravity would vary inversely with the surface area of the sphere, or $4\pi r^2$. This is the logic behind the inverse square law. Now imagine that another dimension is added. In this case, the gravitational field lines would filter into the extra dimension and the force of gravity would be spread out over a four-dimensional shell whose surface area increases with the cube of the distance from the object (13). In this case, the force of gravity would follow an inverse cube law. It is easy to see that the more dimensions we add, the greater the force of gravity would be at increasingly small distances from the center.


As our distance from the center increases, the surface area of the sphere increases by the square of that distance.

Gravity is inversely proportional to surface area. When our radius doubles, gravity must spread out over four times the area and hence has one-fourth of its previous strength.

Figure 1. An explanation of gravity's inverse square law. In four dimensions, we would instead have an inverse cube law.

A natural consequence of the existence of hidden spatial dimensions is that in situations where particles are squeezed together in very compact spaces, the gravitational force governing their interactions may be much larger than otherwise expected. As a result, depending on the number and sizes of these extra dimensions, the true values of the critical energy needed for the formation of black holes may be much smaller than the values predicted using conventional physics theory (14). If these values lie within the energy ranges produced inside particle accelerators, then we may indeed be able to produce quantum black holes artificially!

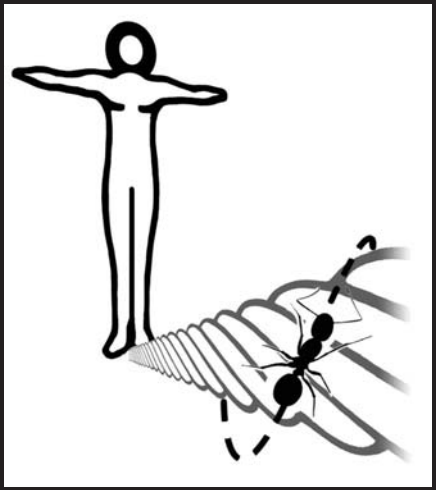


Figure 2. Standing on a thin line, this tightrope walker is limited to one dimension: he may only travel forwards and backwards along the rope.

Unlike the tightrope walker, the tiny ant can travel both along and around the rope. Its world is a rolled up two-dimensional surface, not a one-dimensional line.

credit: Stephanie Zhang, HSR.

So Where's the 9th Dimension Anyway?

The idea of living in a world of multiple hidden dimensions seems counterintuitive to our everyday experiences. All of our major senses seem to tell us that our world is three-dimensional. Moreover, the gravitational laws that exquisitely describe the mechanics of motion appear tailored to a 3-D universe. How can we reconcile our empirical experiences with the claims of string theory and other similar quantum theories of gravity?

One explanation is that according to string theory, of which the simplest forms require nine separate spatial dimensions, the additional dimensions differ from the three spatial dimensions we are intimately familiar with in that they are extremely small and have geometries that hide their presence from our everyday view. To draw an analogy, consider a tightrope walker gingerly making her way across a small piece of rope (Figure 2). From her point of view, it appears as though she is trapped in a one-dimensional world. Our walker can move back and forth along only one axis, such that a single coordinate is sufficient to define her position. But now let us suppose that unbeknownst to all, a mischievous bug is also crawling along the same rope. From the point of view of the bug, the world is not one-dimensional. The bug can move along the rope as well as around the rope. To accurately define the position of the bug, we need three coordinates.

Though not perfect, the tightrope walker analogy illustrates how the world may be fundamentally different at different length scales. The hope of particle physics, and in particular of the quantum black hole experiments, is to probe the world at these finer scales.

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The inquisitive reader may have wondered why so much focus has been placed on detecting the potential effect of extra dimensions on the force of gravity when we have only empirically calculated the gravitational force down to around a tenth of a millimeter. After all, we know much more about the behavior of the other three fundamental forces—the strong nuclear, weak nuclear, and electromagnetic forces—at smaller length scales (13). If extra dimensions indeed exist, why have we not witnessed their effects through the other three forces?

The question is of considerable concern and the answer may betray one of the fundamental differences that sets gravity apart from the other natural forces. It may be that while gravity can seep into these extra dimensions, the respective mediator particles of the other three forces may be trapped inside a three-dimensional membrane, or simply "3-brane" (Figure 3). According to string theory, the photon—the messenger particle of the electromagnetic force—is produced by vibrations of "open" strings in a particular pattern (8). The same is true for gluons and the W and Z bosons, the mediators of the strong and weak nuclear forces, respectively. In contrast, the courier particles of gravity, which are known as gravitons, are produced by vibrations of "closed" strings. The distinction here is that while "open" strings have endpoints that may be confined to the 3-brane, gravitons, being products of "closed" strings, can escape and permeate the other dimensions. As a consequence, the gravitational force may perhaps be the only tool we have with which to probe beyond the 3-brane world.

A 3-brane universe, in which only gravity can escape the impermeable cage of the three-dimensional membrane, poses serious challenges to exploring beyond our three everyday dimensions. Indeed, even if additional dimensions are comparatively large, we still cannot visualize them, precisely because the electromagnetic force with which we "see" cannot penetrate into these higher dimensions. The same is true of many of our other high-powered devices that take advantage of electromagnetism in one way or another. Consequently, our only viable methods of detecting additional dimensions may be through observing gravitational interactions under extreme conditions.

Hence, as we come full circle in our story, it becomes clear why upcoming experiments inside high-powered particle accelerators are so crucial in our understanding of the very makeup of space. If we are fortunate enough to detect the creation and the almost instantaneous evaporation of quantum black holes, we could be almost certain of the existence of hidden dimensions. Furthermore, as black holes decay, some of the energy is inevitably lost as it filters into these extra dimensions. Measuring the change in energy should reveal clues concerning the very nature of this unseen, unexplored universe. As preparations get underway for the next rounds of high-energy particle physics experiments, excitement abounds as the next great chapter in the tale of human discovery may be about to be written. H

—David Mu '07 is a Neurobiology concentrator in Adams House.

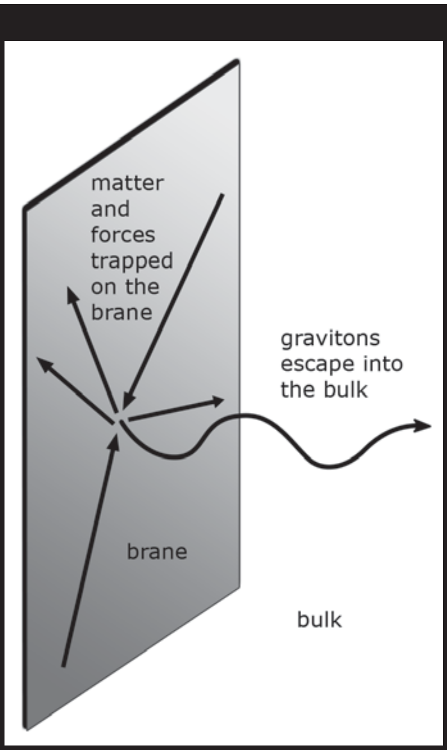

Figure 3. While everything else is trapped on the three-dimensional membrane, gravitons have the ability to escape into the fourth dimension (the bulk).

credit: Adapted from PhysicsWeb.org

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