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Quantum Black Holes

Physicists could soon be creating black holes in the laboratory

BY BERNARD J. CARR& STEVEN B. GIDDINGS

Ever since physicists invented particle accelerators, nearly 80 years ago, they have used them for such exotic tasks as splitting atoms, transmuting elements, producing antimatter and creating particles not previously observed in nature. With luck, though, they could soon undertake a challenge that will make those achievements seem almost pedestrian. Accelerators may produce the most profoundly mysterious objects in the universe: black holes.

When one thinks of black holes, one usually envisions massive monsters that can swallow spaceships, or even stars, whole. But the holes that might be produced at the highest-energy accelerators--perhaps as early as mid-2008, when the Large Hadron Collider (LHC) at CERN near Geneva starts running at full design energy--are distant cousins of such astrophysical behemoths. They would be microscopic, comparable in size to elementary particles. They would not rip apart stars, reign over galaxies or pose a threat to our planet, but in some respects their properties should be even more dramatic. Because of quantum effects, they would evaporate shortly after they formed, lighting up the particle detectors like Christmas trees. In so doing, they could give clues about how space-time is woven together and whether it has unseen higher dimensions.

A Tight Squeeze

IN ITS MODERN FORM, the concept of black holes emerges from Einstein's general theory of relativity, which predicts that if matter is sufficiently compressed, its gravity becomes so strong that it carves out a region of space from which nothing can escape. The boundary of the region is the black hole's event horizon: objects can fall in, but none can come out. In the simplest case, where space has no hidden dimensions or those dimensions are smaller than the hole, its size is directly proportional to its mass. If you compressed the sun to a radius of three kilometers, about four millionths of its present size, it would become a black hole. For Earth to meet the same fate, you would need to squeeze it into a radius of nine millimeters, about a billionth its present size.

Thus, the smaller the hole, the higher the degree of compression that is required to create it. The density to which matter must be squeezed scales as the inverse square of the mass. For a hole with the mass of the sun, the density is about 10^{19} kilograms per cubic meter, higher than that of an atomic nucleus. Such a density is about the highest that can be created through gravitational collapse in the present universe. A body lighter than the sun resists collapse because it gets stabilized by repulsive quantum forces between subatomic particles. Observationally, the lightest black hole candidates are about six solar masses.

Stellar collapse is not the only way that holes might form, however. In the early 1970s Stephen Hawking of the University of Cambridge and one of us (Carr) investigated a mechanism for generating holes in the early universe.

These are termed primordial black holes. As the universe expands, the average density of matter decreases; therefore, the density was much higher in the past, in particular exceeding nuclear levels within the first microsecond of the big bang. The known laws of physics allow for a matter density up to the so-called Planck value of 10^{97} kilograms per cubic meter--the density at which the strength of gravity becomes so strong that quantum-mechanical fluctuations should break down the fabric of spacetime. Such a density would have been enough to create black holes a mere 10^{35} meter across (a dimension known as the Planck length) with a mass of 10^{8} kilogram (the Planck mass).

This is the lightest possible black hole according to conventional descriptions of gravity. It is much more massive but much smaller in size than an elementary particle. Progressively heavier primordial black holes could have formed as the cosmic density fell. Any lighter than 10^{12} kilograms would still be smaller than a proton, but beyond this mass the holes would be as large as more familiar physical objects. Those forming during the epoch when the cosmic density matched nuclear density would have a mass comparable to the sun's and so would be macroscopic.

The high densities of the early universe were a prerequisite for the formation of primordial black holes but did not guarantee it. For a region to stop expanding and collapse to a black hole, it must have been denser than average, so density fluctuations were also necessary. Astronomers know that such fluctuations existed, at least on large scales, or else structures such as galaxies and clusters of galaxies would never have coalesced. For primordial black holes to form, these fluctuations must have been stronger on smaller scales than on large ones, which is possible though not inevitable. Even in the absence of fluctuations, holes might have formed spontaneously at various cosmological phase transitions--for example, when the universe ended its early period of accelerated expansion, known as inflation, or at the nuclear density epoch, when particles such as protons condensed out of the soup of their constituent quarks. Indeed, cosmologists can place important constraints on models of the early universe from the fact that not too much matter ended up in primordial black holes.

Going, Going, Gone?

THE REALIZATION that holes could be small prompted Hawking to consider what quantum effects might come into play, and in 1974 he came to his famous conclusion that black holes do not just swallow particles but also spit them out. Hawking predicted that a hole radiates thermally like a hot coal, with a temperature inversely proportional to its mass. For a solar-mass hole, the temperature is around a millionth of a kelvin, which is completely negligible in today's universe. But for a black hole of 10^{12} kilograms, which is about the mass of a mountain, it is 10^{12} kelvins--hot enough to emit both massless particles, such as photons, and massive ones, such as electrons and positrons.

Because the emission carries off energy, the mass of the hole tends to decrease. So a black hole is highly unstable. As it shrinks, it gets steadily hotter, emitting increasingly energetic particles and shrinking faster and faster. When the hole shrivels to a mass of about 10^6 kilograms, the game is up: within a second, it explodes with the energy of a million-megaton nuclear bomb. The total time for a black hole to evaporate away is proportional to the cube of its initial mass. For a solar-mass hole, the lifetime is an unobservably long 10^{64} years. For a 10^{12}-kilogram one, it is 10^{10} years--about the present age of the universe. Hence, any primordial black holes of this mass would be completing their evaporation and exploding right now. Any smaller ones would have evaporated during an earlier cosmological epoch.

Hawking's work was a tremendous conceptual advance because it linked three previously disparate areas of physics: general relativity, quantum theory and thermodynamics. It was also a step toward a full quantum theory of gravity. Even if primordial black holes never actually formed, thinking about them has led to remarkable physical insights. So it can be useful to study something even if it does not exist.

In particular, the discovery opened up a profound paradox that aims at the heart of why general relativity and quantum mechanics are so hard to reconcile. According to relativity theory, information about what falls into a black hole is forever lost. If the hole evaporates, however, what happens to the information contained within? Hawking suggested that black holes completely evaporate, destroying the information and violating the basic tenets of quantum mechanics. But such destruction of information also conflicts with the law of energy conservation, making this possibility implausible.

One alternative, that evaporating black holes leave behind remnants, is equally unpalatable. For these remnants to encode all the information that could have gone into the black hole, they would have to come in an infinite variety of types. The laws of physics predict that the rate of production of a particle is proportional to the number of types of that particle. Therefore, the black hole remnants would be produced at an infinite rate; even such everyday physical processes as turning on a microwave oven would generate them. Nature would be catastrophically unstable. A third (and most likely) possibility is that information escapes through a breakdown of locality--the notion that events at spatially separated points can influence one another only after light has had time to travel between them--that is more profound than ordinary quantum nonlocality. This conundrum challenges theorists to this day.

Looking for Holes

PROGRESS IN PHYSICS usually requires some guidance from experiment, so the questions raised by microscopic black holes motivate an empirical search for them. One possibility is that astronomers might be able to detect primordial black holes with an initial mass of 10^{12} kilograms exploding in the present universe. Roughly a tenth of the mass of these holes would go into gamma rays. In 1976 Hawking and Don Page, then at the California Institute of Technology, realized that gamma-ray background observations place stringent upper limits on the number of such holes. They could not, for example, constitute a significant amount of the universe's dark matter, and their explosions would rarely be close enough to be detectable. In the mid-1990s, however, David Cline of the University of California, Los Angeles, and his colleagues suggested that the shortest gamma-ray bursts might be primordial black holes blowing up. Although longer bursts are thought to be associated with exploding or merging stars, the short events may have another explanation. Future observations should settle this issue, but the possibility that astronomical observations could probe the final stages of black hole evaporation is tantalizing.

The production of black holes by particle accelerators is an even more exciting possibility. When it comes to producing high densities, no device outdoes accelerators such as the LHC and the Tevatron at Fermi National Accelerator Laboratory in Batavia, Ill. These machines accelerate subatomic particles, such as protons, to velocities exceedingly close to the speed of light. The particles then have enormous kinetic energies. At the LHC, a proton will reach an energy of roughly seven tera-electron volts (TeV). In accord with Einstein's famous relation $E = mc^2$, this energy is equivalent to a mass of 10^{23} kilogram, or 7,000 times the proton's rest mass. When two such particles collide at close range, their energy is concentrated into a tiny region of space. So one might guess that, once in a while, the colliding particles will get close enough to form a black hole.

As it stands, this argument has a problem: a mass of 10^{23} kilogram is far shy of the Planck value of 10^{8} kilogram, which conventional gravity theory implies is the lightest possible hole. This lower limit arises from the uncertainty principle of quantum mechanics. Because particles also behave like waves, they are smeared out over a distance that decreases with increasing energy--at LHC energies, about 10^{19} meter. So this is the smallest region into which a particle's energy can be packed. It allows for a density of 10^{34} kilograms per cubic meter, which is high but not high enough to create a hole. For a particle to be both energetic enough and compact enough to form a black hole, it must have the Planck energy, a factor of 10^{15} beyond the energy of the LHC. Interestingly, accelerators may be able to create objects mathematically related to black holes. The Relativistic Heavy Ion Collider at Brookhaven National Laboratory in Upton, N.Y., may already have done so, but black holes themselves appear to lie out of reach.

Reaching into Other Dimensions

OVER THE PAST DECADE, however, physicists have realized that the standard estimate of the necessary Planckian density could be too high. String theory, one of the leading contenders for a quantum theory of gravity, predicts that space has dimensions beyond the usual three. Gravity, unlike other forces, should propagate into these dimensions and, as a result, grow unexpectedly stronger at short distances. In three dimensions, the force of gravity quadruples as you halve the distance between two objects. But in nine dimensions, gravity would get 256 times as strong. This effect can be quite important if the extra dimensions of space are sufficiently large, and it has been widely investigated in the past few years. There are also other configurations of extra dimensions, known as warped compactifications, that have the same gravity-magnifying effect and may be even more likely to occur if string theory is correct; these have been extensively studied in recent years.

This enhanced growth of the strength of gravity means that the true energy scale at which the laws of gravity and quantum mechanics clash--and black holes can be made--could be much lower than the traditional expectation. Although no experimental evidence yet supports this possibility, the idea sheds new light on various theoretical conundrums. And if it is true, the density required to create black holes could lie within the range of the LHC.

The theoretical study of black hole production in high-energy collisions goes back to the work of Roger Penrose of the University of Oxford in the mid-1970s and Peter DEath and Philip Norbert Payne, both then at Cambridge, in the early 1990s. The newfound possibility of large extra dimensions breathed new life into these investigations and motivated Tom Banks of the University of California, Santa Cruz, and Rutgers University and Willy Fischler of the University of Texas at Austin to write a 1999 paper with a preliminary discussion of black hole production.

At a 2001 workshop two groups--one of us (Giddings), with Scott Thomas, then at Stanford University, and Savas Dimopoulos of Stanford, with Greg Landsberg of Brown University--independently described the observable effects, and thus the potential for discovery, of black hole production at particle colliders such as the LHC. After a few calculations, we were astounded. Rough estimates indicated that under the most optimistic scenarios, corresponding to the lowest plausible value for the Planck scale, black holes could be produced at the rate of one per second. Physicists refer to an accelerator producing a particle at this rate as a factory, so the LHC would be a black hole factory.

The evaporation of these holes would leave very distinctive imprints on the detectors. Typical collisions produce moderate numbers of high-energy particles, but a decaying black hole is different. According to Hawking's work, it radiates a large number of particles in all directions with very high energies. The decay products include all the particle species found in nature. Several research groups have since done increasingly detailed investigations into the remarkable signatures that black holes would produce in the detectors at the LHC.

Is It Raining Black Holes?

THE PROSPECT of producing black holes on Earth may strike some as folly. How do we know that they would safely decay, as Hawking predicted, instead of continuing to grow, eventually consuming the entire planet? At first glance, this seems like a serious concern, especially given that some details of Hawking's original argument may be incorrect--specifically the claim that information is destroyed in black holes.

But general quantum reasoning implies that microscopic black holes cannot be stable and therefore are safe. Concentrations of mass energy, such as elementary particles, are stable only if a conservation law forbids their decay; examples include the conservation of electric charge and of baryon number (which, unless it is somehow violated, assures the stability of protons). There is no such conservation law to stabilize a small black hole. In quantum theory, anything not expressly forbidden is compulsory, so small black holes will rapidly decay, in accord with the second law of thermodynamics.

Indeed, high-energy collisions such as those at the LHC have already taken place--for example, in the early universe and even now, when sufficiently high energy cosmic rays hit our atmosphere. So if collisions at LHC energies can make black holes, nature has already been harmlessly producing them right over our heads. Early estimates by Giddings and Thomas indicated that the highest-energy cosmic rays--protons or heavier atomic nuclei with energies of up to 10^9 TeV--could produce as many as 100 black holes in the atmosphere a year.

In addition, they--along with David Dorfan of U.C. Santa Cruz and Tom Rizzo of the Stanford Linear Accelerator Center and, independently, Jonathan L. Feng of the University of California, Irvine, and Alfred D. Shapere of the University of Kentucky--have discovered that collisions of cosmic neutrinos might be even more productive. If so, the new Auger cosmic-ray observatory in Argentina, which is now taking data, and the upgraded Fly's Eye observatory in Utah may be able to see upward of several holes a year. These observations, however, would not obviate the need for accelerator experiments, which could generate holes more reliably, in greater numbers and under more controlled circumstances.

Producing black holes would open up a whole new frontier of physics. Their mere presence would be compelling evidence of the previously hidden dimensions of space, and by observing their properties, physicists might begin to explore the geographic features of those dimensions. For example, as accelerators manufacture black holes of increasing mass, the holes would poke further into the extra dimensions and could become comparable in size to one or more of them, leading to a distinctive change in the dependence of a hole's temperature on mass. Likewise, if a black hole grows large enough to intersect a parallel three-dimensional universe in the extra dimensions, its decay properties would suddenly change.

Producing black holes in accelerators would also represent the end of one of humankind's historic quests: understanding matter on ever finer scales. Over the past century, physicists have pushed back the frontier of the small--from dust motes to atoms to protons and neutrons to quarks. If they can create black holes, they will have reached the Planck scale, which is believed to be the shortest meaningful length, the limiting distance below which the very notions of space and length probably cease to exist. Any attempt to investigate the possible existence of shorter distances, by performing higher-energy collisions, would inevitably result in black hole production. Higher-energy collisions, rather than splitting matter into finer pieces, would simply produce bigger black holes. In this way, the appearance of black holes would mark the close of a frontier of science. In its place, however, would be a new frontier, that of exploring the geography of the extra dimensions of space.

THE AUTHOR

BERNARD J. CARR and *STEVEN B. GIDDINGS* first met in person at a conference to celebrate Stephen Hawking's 60th birthday in 2002. Carr traces his enthusiasm for astrophysics to the famous 1969 BBC television documentary by Nigel Calder entitled *The Violent Universe*. He became a graduate student of Hawking's in the 1970s, was one of the first scientists to investigate small black holes and today is professor at Queen Mary, University of London. Giddings caught the physics bug when his father first told him about the weird properties of quantum mechanics. He went on to become an expert on quantum gravity and cosmology, was among the first to study the possibility of creating black holes in particle accelerators and is now professor at the University of California, Santa Barbara. When not theorizing about gravity, he struggles against it by rock climbing.

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