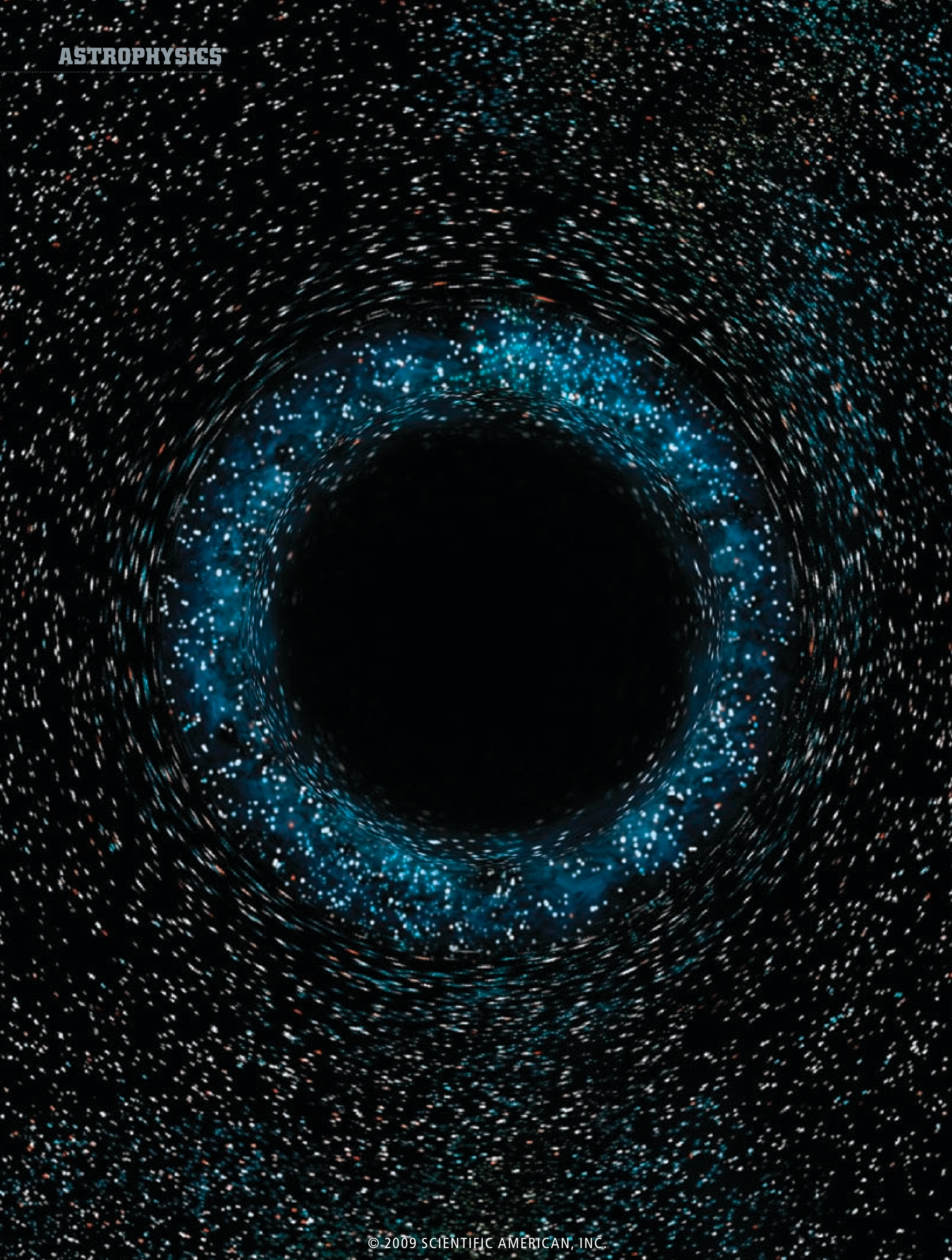
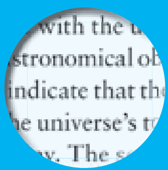


BLACK STARS, NOT HOLES



Quantum effects may prevent true black holes from forming and give rise instead to dense entities called black stars

BY CARLOS BARCELÓ, STEFANO LIBERATI, SEBASTIANO SONEGO AND MATT VISSER

Black holes have been a part of popular culture for decades now, most recently playing a central role in the plot of this year's *Star Trek* movie. No wonder. These dark remnants of collapsed stars seem almost designed to play on some of our primal fears: a black hole harbors unfathomable mystery behind the curtain that is its "event horizon," admits of no escape for anyone or anything that falls within, and irretrievably destroys all it ingests.

To theoretical physicists, black holes are a class of solutions of the Einstein field equations, which are at the heart of his theory of general relativity. The theory describes how all matter and energy distort spacetime as if it were made of elastic and how the resulting curvature of spacetime controls the motion of the matter and energy, producing the force we know as gravity. These equations unambiguously predict that there can be regions of spacetime from which no signal can reach distant observers. These regions—black holes—consist of a location where matter densities approach infinity (a "singularity") surrounded by an empty zone of extreme gravitation from which nothing, not even light, can escape. A conceptual boundary, the event horizon, separates the zone of intense gravitation from the rest of spacetime. In the simplest case, the event horizon is a sphere—just six kilometers in diameter for a black hole of the sun's mass.

So much for fiction and theory. What about reality? A wide variety of high-quality astrophysical observations indicates that the universe does contain some extremely compact bodies that emit essentially no light or other radiation of their own. Although these dark objects have masses ranging from just a few suns to well over a million suns, their diameters, as best astrophysicists can determine, range from only several kilometers to millions of kilometers—matching general relativity's predictions for black holes of those masses.

Yet are these dark and compact bodies that astronomers observe really the black holes predicted by general relativity? The observations to date certainly fit the theory quite well, but the theory itself is not entirely satisfactory in the way that it describes black holes. In particular, general relativity's prediction that a singularity resides inside every black hole suggests that the theory fails at that location, as is usually the case when a theory predicts that some quantity is infinite. Presumably general relativity fails by not

KEY CONCEPTS

- Black holes are theoretical structures in spacetime predicted by the theory of general relativity. Nothing can escape a black hole's gravity after passing inside its event horizon.
- Approximate quantum calculations predict that black holes slowly evaporate, albeit in a paradoxical way. Physicists are still seeking a full, consistent quantum theory of gravity to describe black holes.
- Contrary to physicists' conventional wisdom, a quantum effect called vacuum polarization may grow large enough to stop a hole forming and create a "black star" instead.

—The Editors

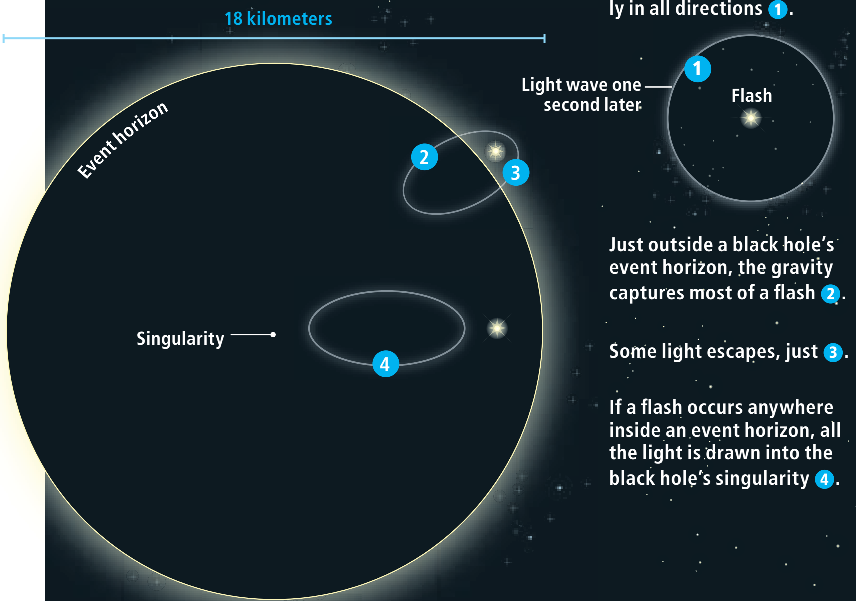
EUROPEAN SPACE AGENCY, NASA AND FELIX MIRABEL
French Atomic Energy Commission, Institute for Astronomy and Space Physics/Conicet of Argentina

[BASICS]

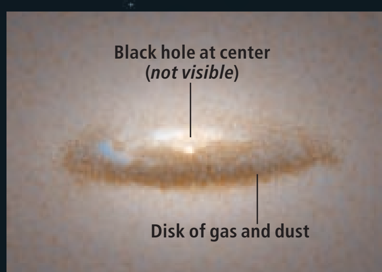
BLACK HOLES IN BRIEF

A black hole is a region of curved spacetime with such intense gravity that nothing can escape. Its defining feature is its event horizon: the boundary of the region of no escape. A black hole is mostly empty, its mass apparently collapsed to a location with infinite density—a "singularity"—deep inside the horizon.

A black hole with three times the mass of the sun would have a diameter of about 18 kilometers, comparable to the length of Manhattan.



▶ In practice, black holes can be observed via the material orbiting and falling into them. The image at the right, taken in 1998 by the Hubble Space Telescope, shows a vast disk of gas and dust believed to have a supermassive black hole at its center. Strictly speaking, however, such observations inform scientists only that an extremely compact, heavy object emitting little or no light of its own is present; they do not provide absolute proof that the object is a black hole.



taking into account quantum effects, which matter and energy exhibit at the microscopic scale. The search for a modified theory that incorporates quantum mechanics, generically called quantum gravity, is a powerful engine driving a lot of activity in theoretical physics research.

This need for a quantum theory of gravity raises fascinating questions: What would quantum-corrected black holes be like? Would they be radically different from classical black holes, or would their classical description remain a good approximation? The four of us have shown that certain quantum effects may well prevent black holes from forming at all. Instead a kind of object we have named a black star could arise. A black star would be blocked from taking the final plunge to infinite density and from becoming enveloped in an event horizon. The black star would be supported by something not normally considered to be a sturdy construction material: space itself.

The Weight of Quantum Nothingness

We derive our conclusions by applying a venerable approach known as semiclassical gravity, but without making all the same assumptions about the collapsing matter that previous studies have made—to see if we might avoid the paradoxical territory arrived at by those studies. In the absence of a full-fledged theory of quantum gravity, theorists have resorted to semiclassical gravity over the past 30-odd years to analyze how quantum mechanics alters black holes. This method partially incorporates aspects of quantum physics—in particular, quantum field theory—into classical Einsteinian gravity.

Quantum field theory describes each kind of fundamental particle—the electron, the photon, quarks, you name it—in terms of a field that fills space, much like the electromagnetic field. Quantum field theory's equations are usually set up in flat spacetime, that is, in the absence of gravity. Semiclassical gravity uses quantum field theory as formulated in curved spacetime.

In the broadest terms, the strategy of semiclassical gravity goes as follows: a collection of matter in some configuration would, according to classical general relativity, produce some specific curved spacetime. Yet the curvature of spacetime modifies the energy of the quantum fields. This modified energy, according to classical general relativity, changes spacetime's curvature. And so on, iteration after iteration.

The goal is to obtain a self-consistent solution—a curved spacetime containing a configuration of quantum fields whose energy generates that same curvature. That kind of self-consistent solution ought to be a good approximation to how reality behaves in many situations involving quantum effects and gravity even though gravity itself has not been described by a quantum theory. Semiclassical gravity thus incorporates quantum corrections into general relativity in a "minimal" way, taking into account the quantum behavior of matter but still treating gravity (that is, spacetime curvature) classically.

This approach, however, immediately runs into an embarrassing problem in that the straightforward calculation of the quantum fields' lowest possible (or "zero point") energy—the energy when no particles of any kind are present, the en-

LUCY READING-IKKANDA (*illustration*); NASA, ROELAND P. VAN DER MAREL *Space Telescope Institute* AND FRANK C. VAN DEN BOSCH *University of Washington* (*dust disk around black hole*) ergy of the vacuum—produces an infinite result. This problem actually comes up already with ordinary quantum field theory (that is, in flat space, no gravity). Fortunately for theorists wishing to predict particle physics phenomena that do not involve gravity, the particles behave in ways that depend on only the energy differences between states, so the value of the quantum vacuum energy plays no role. Careful subtraction schemes known as renormalization take care of the infinities, allowing the energy differences to be computed with extremely high precision.

With gravity in the picture, however, the vacuum energy matters. An infinite energy density would seem to produce an extremely large curvature of spacetime—that is, even "empty" space would harbor an intense gravitational force, which is not remotely compatible with the universe that we actually observe. Astronomical observations over the past decade indicate that the net zero-point contribution to the universe's total energy density is extremely tiny. The semiclassical gravity approach does not attempt to solve this problem. Instead it is customary to assume that *whatever* the solution is, it exactly cancels the zero-point contribution to the energy density in flat spacetime. This assumption makes for a consistent semiclassical vacuum: the energy density is zero everywhere, for which general relativity predicts flat spacetime.

If some matter is present, spacetime is curved, which alters the quantum fields' zero-point energy density, which means the zero-point energy is no longer exactly canceled. The excess amount is said to be caused by vacuum polarization, by analogy with the effect of an electric charge polarizing a medium [*see box on next page*].

We have described these features of semiclassical gravity in terms of mass and energy density, but in general relativity it is not only those quantities that produce spacetime curvature. The momentum density and the pressures and stresses associated with a specific gravitating substance also do so. A single mathematical-physics object, known as the stress energy tensor (SET), describes all these curvature-producing quantities. Semiclassical gravity assumes that the quantum fields' zero-point contributions to the total SET are exactly canceled in flat spacetime. The mathematical-physics object obtained applying such a subtraction procedure to the SET is called the renormalized stress energy tensor (RSET).

BLACK HOLE CATEGORIES

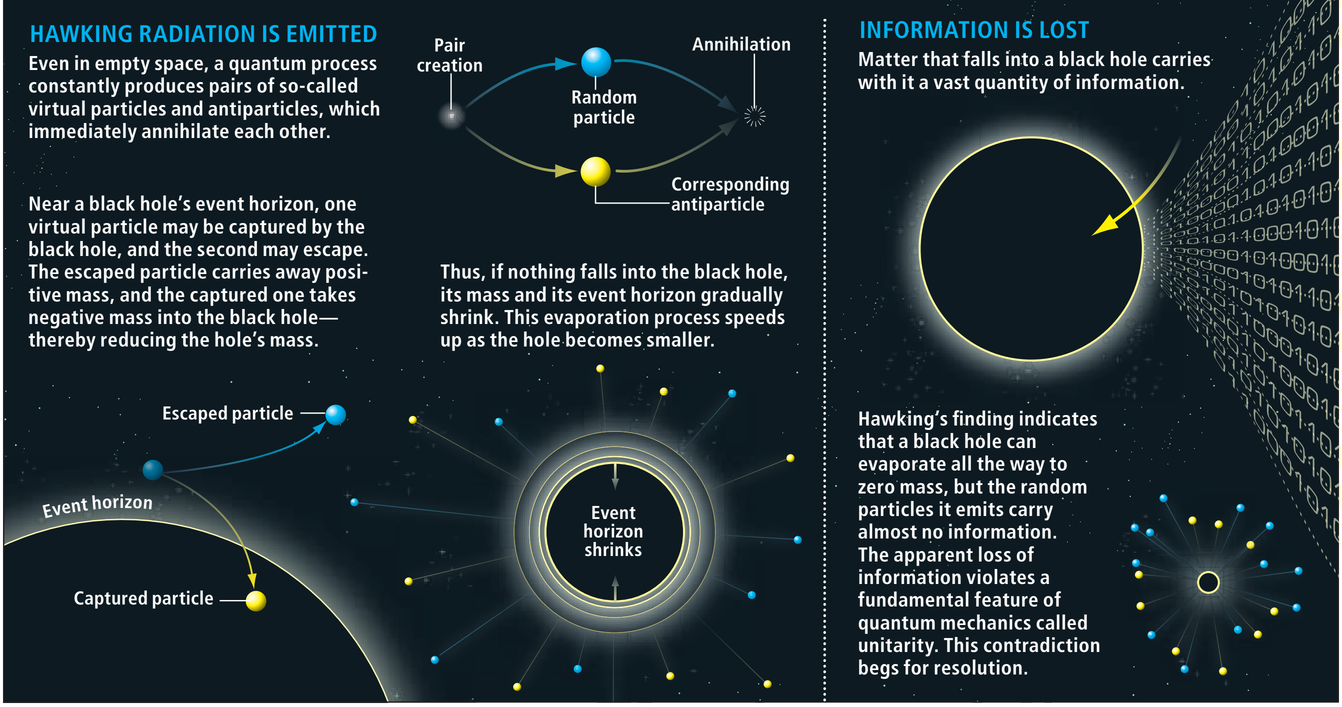
General relativity predicts that a black hole is completely defined by just three quantities: mass, angular momentum and electric charge. It makes no difference what went into the hole—matter, antimatter or energy, or all three combined.

Astronomers have observed holes in three mass classes: Holes of about five to 15 solar masses are formed from dying stars. Many galaxies harbor a hole of millions to billions of solar masses at their core. Holes of a few thousand solar masses have been detected in the center of globular star clusters.

[PARADOX]

THE TROUBLE WITH QUANTUM BLACK HOLES

The classical (that is, nonquantum) equations of general relativity forbid anything emerging from inside a black hole's event horizon. Yet in the 1970s Stephen W. Hawking carried out quantum calculations that predicted black holes would randomly emit particles at a very low rate (*left panel*). The randomness created a paradoxical scenario (*right panel*) known as the information problem.



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[QUANTUM PRIMER]

WHAT EMPTINESS CAN DO

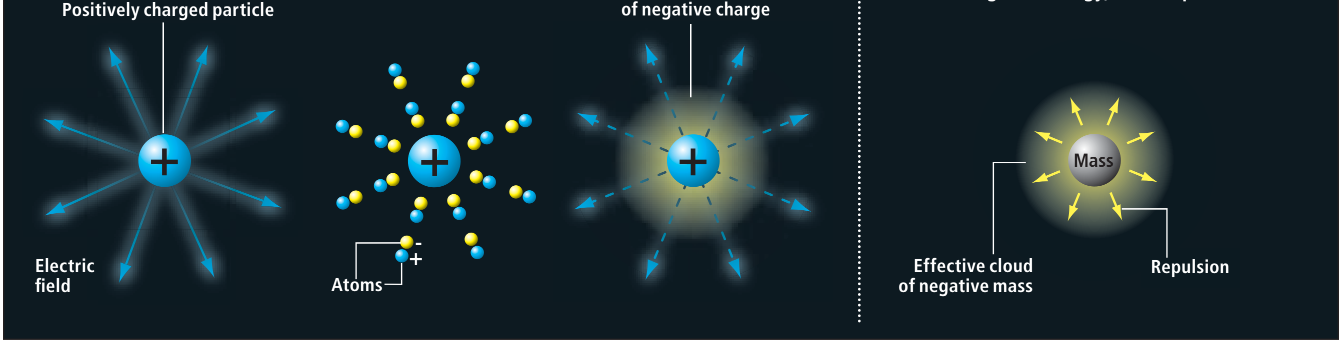
In classical general relativity, spacetime is dynamic, its curvature producing gravity. A quantum effect known as vacuum polarization provides another way that empty space can play an active role in the universe.

ELECTRIC ANALOGY

In a medium, a charged object's electric field (*left*) polarizes nearby atoms (*center*), reducing the total electric field (*right*). Quantum field theory reveals that even a vacuum can be polarized, because an electric field polarizes virtual particle/antiparticle pairs.

VACUUM POLARIZATION

In general relativity, the role of electric charge is played by mass and energy and that of the electric field by curved spacetime, or gravity. The vacuum polarization produces an energy deficit (in effect a cloud of negative energy) and a repulsive force.



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When applied in curved spacetime, the subtraction scheme still succeeds in canceling the SET's divergent part but leaves a finite, nonzero value for the RSET. The end result is the following iterative process: classical matter curves spacetime via Einstein's equations, by an amount determined by the matter's classical SET. This curvature makes the quantum vacuum acquire a finite nonzero RSET. This vacuum RSET becomes an additional source of gravity, modifying the curvature. The new curvature induces in turn a different vacuum RSET, and so on.

Quantum-Corrected Black Holes

With the approach of semiclassical gravity spelled out, the question becomes: How do these quantum corrections affect predictions about black holes? In particular, how do the corrections alter the process of forming a black hole?

The simplest black hole of some mass (say, M times the solar mass) is one that is not rotating and not electrically charged. Such a hole has a radius R that works out to be $3M$ kilometers. The radius R is called the gravitational radius or Schwarzschild radius for that mass. If for any reason some matter has collapsed to occupy a region smaller than its gravitational radius, it has formed a black hole; it has disappeared inside its own event horizon.

The sun, for instance, has a 700,000-kilometer radius, which is much larger than its gravitational radius (three kilometers). The relevant semiclassical gravity equations make it clear that the RSET of the quantum vacuum in this situation is negligible. Thus, the sun is far from forming a black hole according to the classical equations, and quantum corrections do not alter this picture. Indeed, astrophysicists can safely ignore quantum gravity effects when analyzing the sun and most other astronomical objects.

The quantum corrections can become significant, however, if a star is not much larger than its gravitational radius. In 1976 David G. Boulware, now at the University of Washington, analyzed the case of such a compact star when the star is stationary (that is, not collapsing). He showed that the closer the star is to its gravitational radius, the larger the vacuum RSET near its surface becomes, increasing to infinite energy density. This result implies that semiclassical gravity theory does not permit a stationary black hole (meaning one whose event horizon remains constant in size) as a solution of its equations.

Boulware's result, however, does not tell us what to expect in the case of a star undergoing a collapse that would lead to a black hole according to classical general relativity. Stephen W. Hawking had already tackled this situation a year earlier, using somewhat different techniques, to show that a classical black hole formed by collapse emits random particles. More precisely, the particles have a distribution of energies characteristic of thermal radiation; the black hole has a temperature. He conjectured that quantum-corrected black holes would be essentially classical black holes subject to slow evaporation via this radiation. A black hole of one solar mass has a temperature of 60 nanokelvins. The corre-

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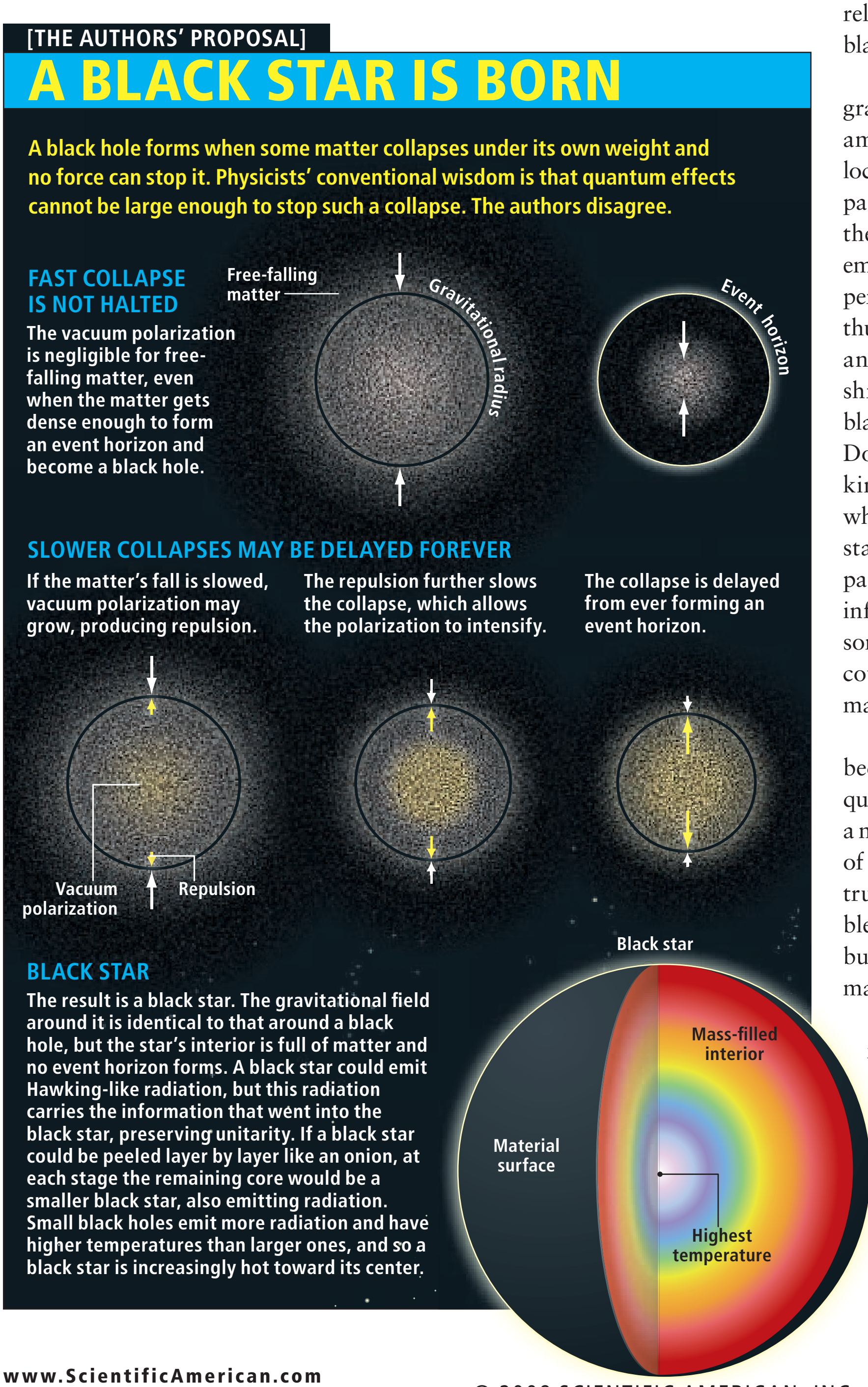
sponding evaporation rate is so slow that absorption of cosmic background radiation would completely overwhelm the evaporation and the hole would grow in size. An evaporating black hole of such a mass would be indistinguishable from a classical black hole in practice because the evaporation would be immeasurably small.

Considerable effort by theorists in the decade after Hawking's paper, including the approximate calculation of the RSET in collapsing configurations, reinforced this picture as being the correct one. Today the standard view in the physics community is that black holes form as described by classical general relativity and subsequently undergo slow quantum evaporation via Hawking radiation.

Quantum matter always seems to find new ways of delaying gravitational collapse.



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The Information Problem

Hawking's discovery of black hole evaporation, along with earlier results by Jacob D. Bekenstein of the Hebrew University of Jerusalem uncovered a deep—and as yet not fully understood—relation among gravity, quantum physics and thermodynamics. At the same time, it opened up new problems. Perhaps the most important is known as the information problem, which is closely related to the question of the final outcome of black hole evaporation.

Take the example of a large star undergoing gravitational collapse. The star embodies a vast amount of information in the positions and velocities and other properties of its more than 10^{55} particles. Suppose the star forms a black hole but then, gradually over the aeons, evaporates by emitting Hawking radiation. A black hole's temperature is inversely proportional to its mass, and thus an evaporating black hole becomes hotter and evaporates faster as its mass and radius shrink. A huge explosion ejects the last of the black hole's mass. But what remains afterward? Does the hole completely vanish, or does some kind of small remnant remain? In either case, what has happened to all the information of the star? According to Hawking's calculation, the particles radiated by the hole carry essentially no information about the star's initial state. Even if some kind of black hole remnant remains, how could such a small object contain all the information that was in the original star?

The disappearance of information matters because one of the most fundamental pillars of quantum theory is that quantum states evolve in a manner that is called unitary, one consequence of which is that no information ought to ever be truly obliterated. Information may be inaccessible in practice, such as when an encyclopedia burns up, but in principle the information remains in the swirling smoke and ashes.

Because the calculations that predict Hawking radiation rely on semiclassical gravity, physicists cannot be sure if information loss is an artifact of the approximations involved or a feature that will remain when we discover how to compute the process exactly. If the evaporation process does destroy information, the correct full quantum gravity equations must violate the unitary nature of quantum mechanics as we know it. Conversely, if information is preserved and a complete theory of quantum gravity will reveal where it is in the radiation, either general relativity or quantum mechanics seems to need modification.

A Radically Different Alternative

The information problem and related puzzles have motivated us (and others) to revisit the line of reasoning that led physicists in the 1970s to the picture of evaporating almost classical black holes. We have found that the old semiclassical prediction that black holes form from gravitational collapse even when quantum effects are considered depends on several technical and often unstated assumptions.

In particular, the old calculations assume that collapse proceeds very rapidly, taking about the same time as would be needed for material at the star's surface to free-fall to the star's center. We found that for a slower collapse, quantum effects may produce a new kind of very compact object that does not have an event horizon and is thus much less problematic.

As we have already mentioned, the RSET of the quantum vacuum in a spacetime curved by a typical star is negligible everywhere. When the star starts to collapse, the RSET might change. Nevertheless, the old conclusion that the RSET remains negligible continues to hold if the collapse is about as fast as free falling.

Yet if the collapse proceeds significantly slower than free falling, the RSET can acquire arbitrarily large and negative values in the region near the Schwarzschild radius—where the classical event horizon would have formed. A negative RSET produces a repulsion, which further slows the collapse. The collapse might come to a complete halt just short of forming a horizon, or it might continue forever at an ever slower pace, becoming ever closer to forming a horizon but never actually producing one.

This result, however, does not make it impossible for black holes to form. A perfectly homogeneous spherical cloud of matter of, say, 100 million solar masses falling freely under its own weight would surely produce an event horizon. Such a large cloud would have a density comparable to that of water when it became compact enough to form a horizon. At such a low density the RSET cannot become large enough to prevent the horizon from forming. But we know that what happened in the universe did not follow this script. The vast, nearly homogeneous clouds of matter that emerged from the early stages of the big bang did not collapse to form black holes. Instead a sequence of structures developed.

First, stars formed, the heat of their nuclear reactions delaying the collapse for a long time. When a star largely exhausts its nuclear fuel, it may develop into a white dwarf or, if massive enough, explode as a supernova, leaving behind a neutron star (a sphere made of neutrons that is only somewhat larger than the star's gravitational radius). In either case,

[ALTERNATIVE BODIES]

OTHER WAYS OUT OF A HOLE

Many researchers have proposed more or less exotic objects that could serve as alternatives to the conventional (but apparently paradoxical) idea of an evaporating black hole and account for the dark, compact bodies observed by astronomers. The common feature of these proposals (and our own black star hypothesis) is that the new object would lack an event horizon.

GRAVASTARS

The spacetime geometry around a "*gra*vitational *va*cuum *star*" would be indistinguishable from that of a black hole down to about 10^{-35} meter away from the spherical region where the classical black hole horizon would have been located. The horizon would be replaced by a shell of matter and energy a mere 10^{-35} meter thick (known as the Planck length—the length scale at which quantum gravity effects are expected to become large). The gravastar's interior would be empty space with a large vacuum polarization, which would produce a repulsion that prevents the matter shell from collapsing any further. In a variant of the gravastar proposal, the classical notions of geometry break down in the region separating the interior and exterior.

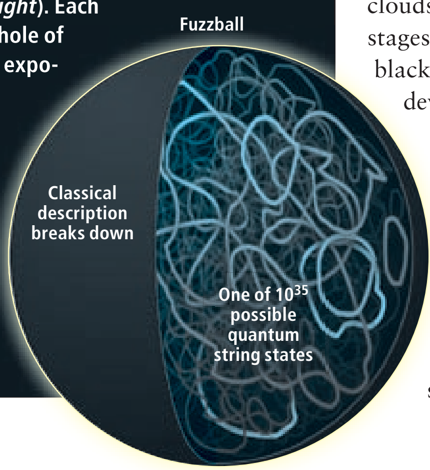
BLACK HOLE COMPLEMENTARITY

In conventional quantum mechanics, complementarity refers to the idea that an observation may reveal either the particle nature of an object or the wave nature, but not both. Similarly, the quantum mechanics of black holes might embody a new kind of complementarity. An observer who remains outside a black hole may have one description of the observable geometry (for instance, imagining a membrane having certain physical properties in place of the event horizon), whereas an observer who falls into the hole must use a different description.

FUZZBALLS

Proponents of "fuzzballs" contend that the horizon would be a transition region between the exterior classical geometry and a quantum interior where no definite notion of spacetime could be specified. The interior would be describable by string theory and would not have a singularity (*right*). Each exterior geometry (say, the geometry of a black hole of exactly 10^{30} kilograms) could have any one of an exponentially large number of such stringy quantum states as its interior. The semiclassical view of a black hole—with an event horizon, an enormous entropy, a temperature and emission of thermal Hawking radiation—would amount to a statistical average over all the possible interiors, analogous to a description of a volume of gas that disregards the exact positions and motions of the individual atoms.

—C.B., S.L., S.S. and M.V.



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it is actually a purely quantum effect—the Pauli exclusion principle—that prevents further collapse. The neutrons in the neutron star cannot enter the same quantum state, and the resulting pressure resists the gravitational collapse. A similar story for ions and electrons explains why a white dwarf is stable.

If the neutron star acquires more mass, eventually the crushing gravitational load overwhelms the neutrons, and further collapse occurs. We do not know for certain what happens next (although the conventional view says a black hole forms). Scientists have suggested a variety of objects that might form—such as so-called quark stars, strange stars, boson stars and Q-balls—that would be stable at pressures too great for a neutron star. Physicists must develop a better understanding of how matter behaves at densities well beyond that of neutrons to know which conjecture, if any of them, is correct.

Thus, experience tells us that matter following the laws of quantum mechanics always seems to find new ways of delaying gravitational collapse. Although any of these roadblocks may be overcome (a typical stable configuration can always be made unstable by adding enough matter), each process that delays collapse provides additional time for the quantum vacuum's negative RSET to pile up and become significant. This RSET could take over the task of counterbalancing the gravitational pull, and because its repulsion may increase without limit, it can stop the matter's collapse to a black hole forever.

Black Stars

The resulting bodies would be the new kind of object we have named black stars. Because of their extremely small size and high density, they would share many observable properties with black holes, but conceptually they would be radically different. They would be material bodies, with a material surface and an interior filled with dense matter. They would be extremely dim because light emitted from their surface would be very redshifted—the light wave greatly stretched—in traveling from the intensely curved space near the black star to distant astronomers. In principle, astronomers could conduct complete astrophysical studies of black stars because no event horizon would present an obstacle.

Within the family of bodies of black star type, some might resemble evaporating black holes by emitting radiation similar to Hawking radiation. For the specific case in which collapse approaches formation of a horizon but never quite stops, we have shown that a black star could emit particles with a so-called Planckian energy spectrum (which is very similar to a thermal spectrum), at a temperature very slightly smaller than the Hawking temperature. By having no horizon, the black star cannot lock away any information. Instead the emitted particles and whatever matter remains behind with the black star carry all the information. Standard quantum physics would describe the formation and evaporation process. Black stars do not completely solve the information problem, however, as long as ways remain for event horizons to form somewhere in the universe.

These evaporating objects could be called quasi black holes because when viewed from the outside they would have approximately the same thermodynamic properties as evaporating black holes. Their interiors, however, would harbor a rainbow of temperatures, rising to a maximum near the center. If you imagine the body as an onionlike structure of concentric shells, each shell would be slowly shrinking, never quite compact enough for the combined mass of the shell and everything inside it to form a horizon. Each shell would be prevented from collapsing by the vacuum RSET that we predict will develop where the conditions for a horizon are approached slowly enough. The deeper shells would have higher temperatures, just like smaller-mass black holes do. We do not yet know whether these appealing objects show up naturally or whether they are exceptional.

Over the Horizon

Study of black holes has always provoked a great variety of reactions from researchers. On the one hand, it is exciting to think that they hide within them the door to unforeseeable new possibilities in physics, albeit only for those who dare to enter. On the other hand, implications of black holes have long disturbed some physicists—the quest for alternatives to black holes, often motivated by distaste for one or another of their features, is as old as the idea of black holes themselves.

Our black star proposal and other researchers' black hole alternatives all have the common theme that the spacetime around them is essentially identical to that around a classical black hole, down to extremely close to where the horizon would have formed. Although the secret door leading to an understanding of how quantum physics merges with gravity remains out of our sight, it may not be shielded from us by the impenetrable fortress of an event horizon. ■

WHAT'S NEXT

Future work on the black star scenario must show specific physical systems for which vacuum polarization succeeds in halting a collapse according to semiclassical gravity.

By describing quantum black holes as bundles of fundamental entities called branes, string theorists have reproduced predictions of semiclassical gravity for certain special cases. They hope to extend these results to all kinds of black holes.

A definitive resolution of the information problem and of the fate of collapsing matter will most likely require development of a complete quantum theory of gravity.

➥ MORE TO EXPLORE

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