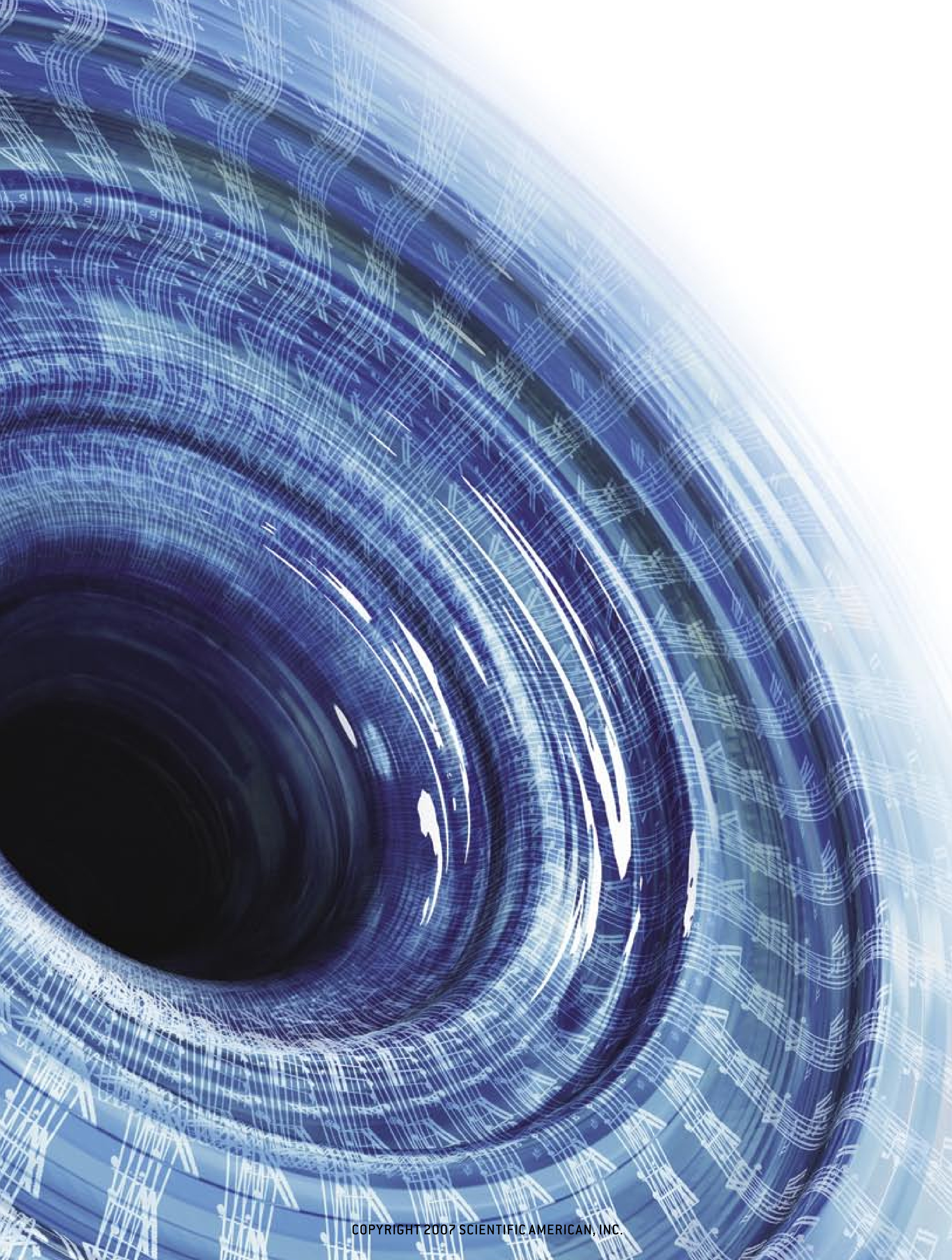

AN ECHO of black holes

Sound waves in a fluid behave uncannily like light waves in space. Black holes even have acoustic counterparts. Could spacetime literally be a kind of fluid, like the ether of pre-Einsteinian physics?

By Theodore A. Jacobson and Renaud Parentani

When Albert Einstein proposed his special theory of relativity in 1905, he rejected the 19th-century idea that light arises from vibrations of a hypothetical medium, the "ether." Instead, he argued, light waves can travel in vacuo without being supported by any material—unlike sound waves, which are vibrations of the medium in which they propagate. This feature of special relativity is untouched in the two other pillars of modern physics, general relativity and quantum mechanics. Right up to the present day, all experimental data, on scales ranging from subnuclear to galactic, are successfully explained by these three theories.

Nevertheless, physicists face a deep conceptual problem. As currently understood, general relativity and quantum mechanics are incompatible. Gravity, which general relativity attributes to the curvature of the spacetime continuum, stubbornly resists being incorporated into a quantum framework. Theorists have made only incremental progress toward understanding the highly curved structure of spacetime that quantum mechanics leads them to expect at extremely short distances. Frustrated, some have turned to an unexpected source for guidance: condensed-matter physics, the study of common substances such as crystals and fluids.

Like spacetime, condensed matter looks like a continuum when viewed at large scales, but unlike spacetime it has a well-understood microscopic structure governed by quantum mechanics. Moreover, the propagation of sound in an uneven fluid flow is closely analogous to the propagation of light in a curved spacetime. By studying a model of a black hole using sound waves, we and our colleagues are attempting to exploit this analogy to gain insight into the possible microscopic workings of spacetime. The work suggests that spacetime may, like a material fluid, be granular and possess a preferred frame of reference that manifests itself on fine scales—contrary to Einstein's assumptions.

From Black Hole to Hot Coal

BLACK HOLES are a favorite testing ground for quantum gravity because they are among the few places where quantum mechanics and general relativity are both critically important. A major step toward a merger of the two theories came in 1974, when Stephen Hawking of the University of Cambridge applied quantum mechanics to the horizon of black holes.

According to general relativity, the horizon is the surface that separates the inside of a black hole (where gravity is so strong that nothing can escape) from the outside. It is not a material limit; unfortunate travelers falling into the hole would not sense anything special on crossing the horizon. But once having done so, they would no longer be able to send light signals to people outside, let alone return there. An outside observer would receive only the signals transmitted by the travelers before they crossed over. As light waves climb out of the gravitational well around a black hole, they get stretched out, shifting down in frequency and lengthening in duration. Consequently, to the observer, the travelers would appear to move in slow motion and to be redder than usual.

This effect, known as gravitational redshift, is not specific to black holes. It also alters the frequency and timing of signals between, say, orbiting satellites and ground stations. GPS navigation systems must take it into account to work accurately. What is specific to black holes, however, is that the redshift becomes infinite as the travelers approach the horizon. From the outside observer's point of view, the descent appears to take an infinite amount of time, even though only a finite time passes for the travelers themselves.

So far this description of black holes has treated light as a classical electromagnetic wave. What Hawking did was to reconsider the implications of the infinite redshift when the quantum nature of light is taken into account. According to quantum theory, even a perfect vacuum is not truly empty;

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RIPPLES IN A STREAM behave much like light waves in spacetime. The flow of the stream around the rock is not uniform, so the ripples are bent and their wavelengths vary. The same happens to light passing through the gravitational field of a planet or star. In some cases, the flow is so fast that ripples cannot propagate upstream—just as light cannot propagate out of a black hole.

BOB FOSBURY

it is filled with fluctuations as a result of the Heisenberg uncertainty principle. The fluctuations take the form of pairs of virtual photons. These photons are called virtual because, in an uncurved spacetime, far from any gravitational influence, they appear and disappear restlessly, remaining unobservable in the absence of any disturbance.

But in the curved spacetime around a black hole, one member of the pair can be trapped inside the horizon while the other gets stranded outside. The pair can then pass from virtual to real, leading to an outward flux of observable light and a corresponding decrease in the mass of the hole. The overall pattern of radiation is thermal, like that from a hot coal, with a temperature inversely proportional to the mass of the black hole. This phenomenon is called the Hawking effect. Unless the hole swallows matter or energy to make up the loss, the Hawking radiation will drain it of all its mass.

An important point—which will become critical later when considering fluid analogies to black holes—is that the space very near the black hole horizon remains a nearly perfect quantum vacuum. In fact, this condition is essential for Hawking's argument. The virtual photons are a feature of the lowest-energy quantum state, or "ground state." It is only in the process of separating from their partners and climbing away from the horizon that the virtual photons become real.

The Ultimate Microscope

HAWKING'S ANALYSIS has played a central role in the attempt to build a full quantum theory of gravity. The ability to reproduce and elucidate the effect is a crucial test for candidate quantum gravity theories, such as string theory. Yet although most physicists accept Hawking's argument, they have never been able to confirm it experimentally. The predicted emission from stellar and galactic black holes is far too feeble to see. The only hope for observing Hawking radiation is to find miniature holes left over from the early universe or created in particle accelerators, which may well prove impossible.

The lack of empirical confirmation of the Hawking effect is particularly vexing in view of the disturbing fact that the theory has potential flaws, stemming from the infinite redshift that it predicts a photon will undergo. Consider what the emission process looks like when viewed reversed in time. As the Hawking photon gets nearer to the hole, it blueshifts to a higher frequency and correspondingly shorter wavelength. The further back in time it is followed, the closer it approaches the horizon and the shorter its wavelength becomes. Once the wavelength becomes much smaller than the black hole, the particle joins its partner and becomes the virtual pair discussed earlier.

The blueshifting continues without abatement, down to arbitrarily short distances. Smaller than a distance of about 10^{-35} meter, known as the Planck length, neither relativity nor standard quantum theory can predict what the particle will do. A quantum theory of gravity is needed. A black hole horizon thus acts as a fantastic microscope that brings the observer into contact with unknown physics. For a theorist, this magnification is worrisome. If Hawking's prediction relies on unknown physics, should we not be suspicious of its validity? Might the properties, even

Overview
Acoustic Black Holes

- The famous physicist Stephen Hawking argued in the 1970s that black holes are not truly black; they emit a quantum glow of thermal radiation. But his analysis had a problem. According to relativity theory, waves starting at a black hole horizon will be stretched by an infinite amount as they propagate away. Therefore, Hawking's radiation must emerge from an infinitely small region of space, where the unknown effects of quantum gravity take over.
- Physicists have grappled with this problem by studying black hole analogues in fluid systems. The fluid's molecular structure cuts off the infinite stretching and replaces the microscopic mysteries of spacetime by known physics.
- The analogies lend credence to Hawking's conclusion. They also suggest to some researchers that spacetime has a "molecular" structure, contrary to the assumptions of standard relativity theory.

the existence, of Hawking radiation depend on the microscopic properties of spacetime—much as, for example, the heat capacity or speed of sound of a substance depends on its microscopic structure and dynamics? Or is the effect, as Hawking originally argued, entirely determined just by the macroscopic properties of the black hole, namely, its mass and spin?

Sound Bites

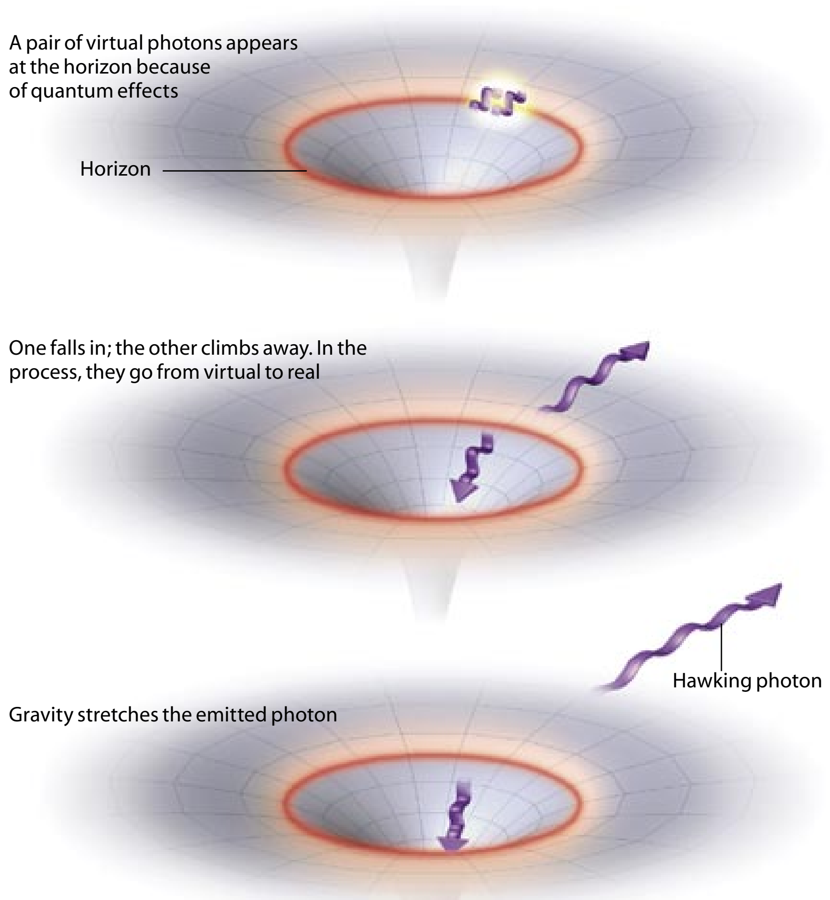
ONE EFFORT TO ANSWER these embarrassing questions began with the work of William Unruh of the University of British Columbia. In 1981 he showed that there is a close analogy between the propagation of sound in a moving fluid and that of light in a curved spacetime. He suggested that this analogy might be useful in assessing the impact of microscopic physics on the origin of Hawking radiation. Moreover, it might even allow for experimental observation of a Hawking-like phenomenon.

Like light waves, acoustic (sound) waves are characterized by a frequency, wavelength and propagation speed. The very concept of a sound wave is valid only when the wavelength is much longer than the distance between molecules of the fluid; on smaller scales, acoustic waves cease to exist. It is precisely this limitation that makes the analogy so interesting, because it can allow physicists to study the macroscopic consequences of microscopic structure. To be truly useful, however, this analogy must extend to the quantum level. Ordinarily, random thermal jigging of the molecules prevents sound waves from behaving analogously to light quanta. But when the temperature approaches absolute zero, sound can behave like quantum particles, which physicists call "phonons" to underline the analogy with the particles of light, photons. Experimenters routinely observe phonons in crystals and in substances that remain fluid at sufficiently low temperatures, such as liquid helium.

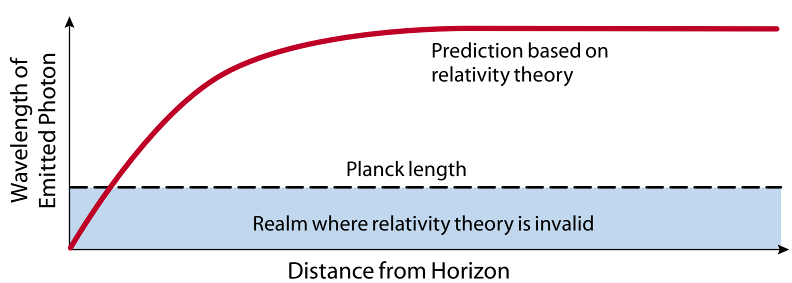
The behavior of phonons in a fluid at rest or moving uniformly is like that of photons in flat spacetime, where gravity is absent. Such phonons propa-

Was Hawking Wrong?

One of the greatest—and least recognized—mysteries of black holes concerns a flaw in Stephen Hawking's famous prediction that black holes emit radiation. A hole is defined by an event horizon, a one-way door: objects on the outside can fall in, but objects on the inside cannot get out. Hawking asked what happens to pairs of virtual particles (which continually appear and disappear everywhere in empty space because of quantum effects) that originate at the horizon itself.



Relativity theory predicts that a photon from the horizon gets stretched by an infinite amount (*red curve, below*). In other words, an observed photon must have originated as a virtual one with a wavelength of almost precisely zero, which is problematic because unknown quantum gravity effects take over at distances shorter than the so-called Planck length of 10^{-35} meter. This conundrum has driven physicists to design experimentally realizable analogues to black holes to see whether they indeed emit radiation and to understand how it originates.



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Light vs. Sound

Type of Wave	Classical Description	Quantum Description	Velocity	What Causes Path of Wave to Curve	Where Description Breaks Down
Light	Oscillating electric and magnetic fields	Electromagnetic-wave photon	300,000 kilometers per second	Spacetime curvature, caused by matter and energy	Planck length? (10^{-35} meter)
Sound	Collective movements of molecules	Acoustic-wave phonon	1,500 meters per second (in liquid water)	Variations in fluid speed and direction	Intermolecular distance (10^{-10} meter for water)

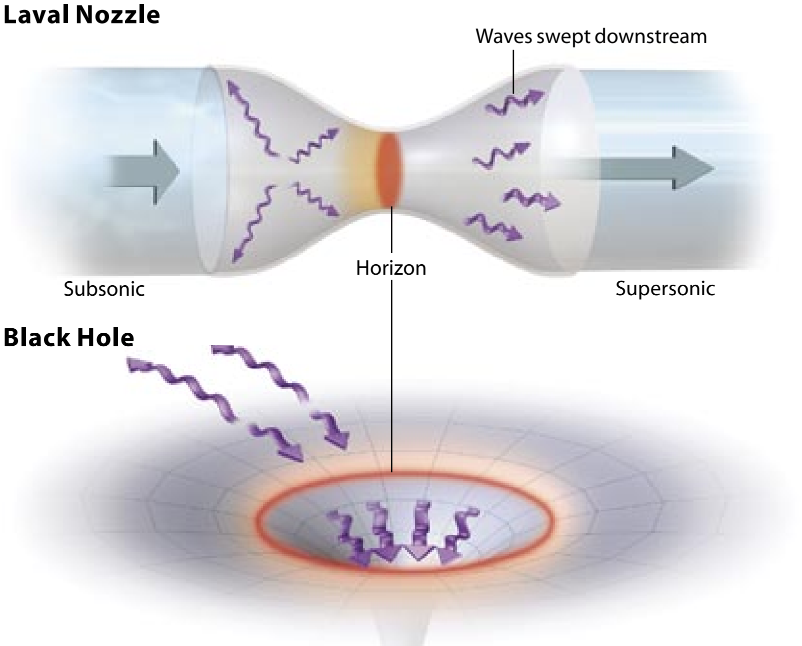
gate in straight lines with unchanging wavelength, frequency and velocity. Sound in, say, a swimming pool or a smoothly flowing river travels straight from its source to the ear.

In a fluid moving nonuniformly, however, the phonons' velocity is altered and their wavelength can become stretched, just like photons in a curved spacetime. Sound in a river entering a narrow canyon or water swirling down the drain becomes distorted and follows a bent path, like light around a star. In fact, the situation can be described using the geometric tools of general relativity.

A fluid flow can even act on sound as a black hole acts on light. One way to create such an acoustic black hole is to use a device that hydrodynamicists call a Laval nozzle. The nozzle is designed so that the fluid reaches the speed of sound at the narrowest point and is supersonic beyond it. The effective acoustic geometry is very similar to the spacetime geometry of a black hole. The supersonic region corresponds to the hole's interior: sound waves propagating against the direction of the flow are swept downstream, like light pulled toward the center of a hole. The subsonic region is the exterior of the hole: sound waves can propagate upstream but only at the expense of being stretched, like light being redshifted. The boundary between the two regions behaves exactly like a black hole horizon.

Black Hole Analogue

A Laval nozzle—found at the end of rockets—makes a ready analogue to a black hole. The incoming fluid is subsonic; the constriction forces it to accelerate to the speed of sound, so that the outgoing fluid is supersonic. Sound waves in the subsonic region can move upstream, whereas waves in the supersonic region cannot. The constriction thus acts just like the horizon of a black hole: sound can enter but not exit the supersonic region. Quantum fluctuations in the constriction should generate sound analogous to Hawking radiation.



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Atomism

IF THE FLUID is cold enough, the analogy extends to the quantum level. Unruh argued that the sonic horizon emits thermal phonons analogous to Hawking radiation. Quantum fluctuations near the horizon cause pairs of phonons to appear; one partner gets swept into the supersonic region, never to return, while the other ripples upstream, getting stretched out by the fluid flow. A microphone placed upstream picks up a faint hiss. The sound energy of the hiss is drawn from the kinetic energy of the fluid flow.

The dominant tone of the noise depends on the geometry; the typical wavelength of the observed phonons is comparable to the distance over which the flow velocity changes appreciably. This distance is much larger than the distance between molecules, so Unruh did his original analysis assuming that the fluid is smooth and continuous. Yet the phonons originate near the horizon with wavelengths so short that they should be sensitive to the granularity of the fluid. Does that affect the end result? Does a real fluid emit Hawking-like phonons, or is Unruh's prediction an artifact of the idealization of a continuous fluid? If that question can be answered for acoustic black holes, it may by analogy guide physicists in the case of gravitational black holes.

Physicists have proposed a number of black hole analogues besides the transsonic fluid flow. One involves not sound waves but ripples on the surface of a liquid or along the interface between layers of superfluid helium, which is so cold that it has lost all frictional resistance to motion. Recently Unruh and Ralf Schützhold of the Technical University of Dresden in Germany proposed to study electromagnetic waves passing through a tiny, carefully engineered electronic pipe. By sweeping a laser along the pipe to change the local wave speed, physicists might be able to create a horizon. Yet another idea is to model the accelerating expansion of the universe, which generates a Hawking-like radiation. A Bose-Einstein condensate—a gas so cold that the atoms have lost their individual identity—can act on sound like an expanding universe does on light, either by literally flying apart or by being manipulated using a magnetic field to give the same effect.

As yet, experimenters have not created any of these devices in the laboratory. The procedures are complicated, and experimenters have plenty of other low-temperature phenomena to keep them busy. So theorists have been working to see whether they can make headway on the problem mathematically.

Understanding how the molecular structure of the fluid affects phonons is extremely complicated. Fortunately, 10 years after Unruh proposed his sonic analogy, one of us (Jacobson) came up with a very useful simplification. The essential details of the molecular structure are encapsulated in the way that the frequency of a sound wave depends on its wavelength. This dependence, called the dispersion relation, determines the velocity of propagation. For large wavelengths, the velocity remains constant. For short wavelengths, approaching the intermolecular distance, the velocity can vary with wavelength.

Three different behaviors can arise. Type I is no dispersion—the wave behaves the same at short wavelengths as it does at long ones. For type II, the velocity decreases as the wavelength decreases, and for type III, velocity increases. Type I describes photons in relativity. Type II describes phonons in, for example, superfluid helium, and type III describes phonons in dilute Bose-Einstein condensates. This division into three types provides an organizing principle for figuring out how molecular structure affects sound on a macroscopic level. Beginning in 1995, Unruh and then other researchers have examined the Hawking effect in the presence of type II and type III dispersion.

Consider how the Hawking-like phonons look when viewed backward in time. Initially the dispersion type does not matter. The phonons swim downstream toward the horizon, their wavelengths decreasing all the while. Once the wavelength approaches the intermolecular distance, the specific dispersion relation becomes important. For type II, the phonons slow down, then reverse direction and start heading upstream again. For type III, they accelerate, break the long-wavelength speed of sound, then cross the horizon.

Ether Redux

A TRUE ANALOGY to the Hawking effect must meet an important condition: the virtual phonon pairs must begin life in their ground state, as do the virtual photon pairs around the black hole. In a real fluid, this condition would be easily met. As long as the macroscopic fluid flow changes slowly in time and space (compared with the pace of events at the molecular level), the molecular state continuously adjusts to minimize the energy of the system as a whole. It does not matter which molecules the fluid is made of.

With this condition met, it turns out that the fluid emits Hawking-like radiation no matter which of the three types

Energy Balance in the Hawking Effect

A common source of confusion in understanding the Hawking effect is how the energy balance is accounted for in the process and what is happening with the "virtual pairs" that are the origin of the radiation. Consider a pair of photons emerging from the vacuum, one outside the horizon with positive energy and the other inside with opposite, negative energy. (The members of a virtual pair must always have opposite values of energy, because the total energy is conserved.) Negative-energy particles cannot exist outside the horizon, because the vacuum is by definition the lowest energy state. Therefore, only a positive-energy photon can escape, whereas its negative-energy partner is trapped inside, lowering the total energy—and therefore the mass—of the black hole.

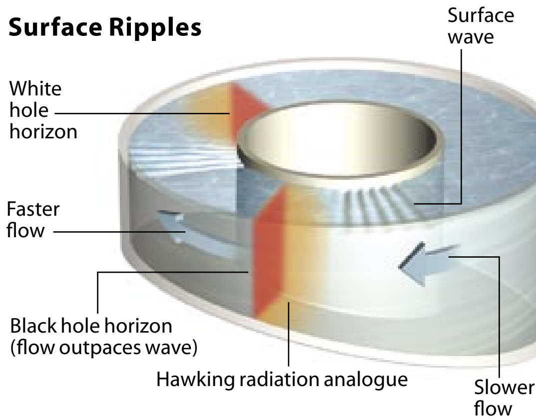
If a negative-energy photon cannot exist outside the horizon, how can it exist inside? Would not that violate the definition of the vacuum, too? To understand why not, we must distinguish between locally measured energy and globally conserved energy. The usual concept of conserved energy is related to time-shift symmetry, whereby the laws of physics are the same at all times. Conserved momentum is related to space-shift symmetry. In a black hole spacetime, the global symmetry that is a temporal shift outside the horizon becomes a spatial shift inside. So the single conserved quantity, the "global energy," corresponds to energy outside and momentum inside. In the Hawking effect, the partner photons inside the horizon have negative "global energy," but their locally measured energy is positive.

In the fluid analogue of a black hole, the energy for the sonic Hawking radiation comes from the kinetic energy of the bulk flow of fluid. A sound wave going upstream saps energy from the flow, but the energy of the wave itself makes up for this, so the total energy is higher—as long as the flow speed is less than the speed of sound. Inside the sonic horizon, the flow speed is greater than the speed of sound. There the wave saps more energy from the flow than it carries itself, so the total energy is less than that of the undisturbed flow. Such a wave can be thought of as containing negative energy. *—T.A.J. and R.P.*

Other Black Hole Models

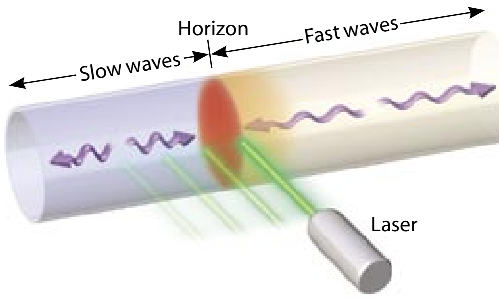
Devices besides the Laval nozzle also reproduce the essential characteristic of a black hole horizon: waves can go one way but not the other. Each offers novel insights into black holes. All should generate the analogue of Hawking radiation.

Surface Ripples



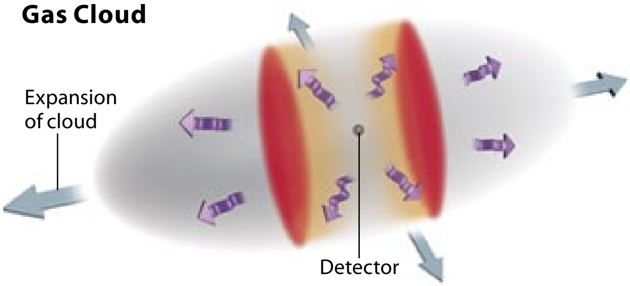
Instead of sound waves, this experiment involves surface waves in liquid flowing around a circular channel. As the channel becomes shallower, the flow speeds up and, at some point, outpaces the waves, preventing them from traveling upstream—thereby creating the analogue of a black hole horizon. Completing the circuit is the horizon of a "white hole": a body that lets material flow out but not in. To observe Hawking-like radiation would require a supercooled fluid such as helium 4.

Electromagnetic-Wave Pipe



This experiment studies microwaves passing through a rod built so that the speed of wave propagation can be tweaked with a laser beam. Sweeping the beam along the rod creates a moving horizon that divides the rod into slow- and fast-wave zones. Waves in the slow zone cannot reach the fast zone, but waves in the fast zone can cross to the slow. The Hawking-like radiation may be stronger and easier to observe than in fluid analogies.

Gas Cloud



The long axis of an inflating, cigar-shaped gas cloud can simulate a one-dimensional universe expanding at an accelerating rate. Such a universe behaves like an inside-out black hole: waves outside the horizons are swept away too quickly to enter the inner region. A Hawking-like radiation should stream inward. In practice, the gas would be a Bose-Einstein condensate, a supercooled gas with quantum properties that make the Hawking analogy possible.

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of dispersion relations applies. The microscopic details of the fluid do not have any effect. They get washed out as the phonons travel away from the horizon. In addition, the arbitrarily short wavelengths invoked by original Hawking analysis do not arise when either type II or III dispersion is included. Instead the wavelengths bottom out at the intermolecular distance. The infinite redshift is an avatar of the unphysical assumption of infinitely small atoms.

Applied to real black holes, the fluid analogy lends confidence that Hawking's result is correct despite the simplifications he made. Moreover, it suggests to some researchers that the infinite redshift at a gravitational black hole horizon may be similarly avoided by dispersion of short wavelength light. But there is a catch. Relativity theory flatly asserts that light does not undergo dispersion in a vacuum. The wavelength of a photon appears different to different observers; it is arbitrarily long when viewed from a reference frame that is moving sufficiently close to the speed of light. Hence, the laws of physics cannot mandate a fixed short-wavelength cutoff, at which the dispersion relation changes from type I to type II or III. Each observer would perceive a different cutoff.

THE AUTHORS

THEODORE A. JACOBSON and *RENAUD PARENTANI* study the puzzles of quantum gravity and its possible observable consequences for black holes and cosmology. Jacobson is a physics professor at the University of Maryland. His recent research focuses on the thermodynamics of black holes, how spacetime might be microscopically discrete and whether that fine structure could be macroscopically detected. Parentani is a physics professor at the University of Paris-Sud at Orsay who does research at the CNRS Laboratory of Theoretical Physics. He investigates the role of quantum fluctuations in black hole physics and cosmology.

Physicists thus face a dilemma. Either they retain Einstein's injunction against a preferred frame and they swallow the infinite redshifting, or they assume that photons do not undergo an infinite redshift and they have to introduce a preferred reference frame. Would this frame necessarily violate relativity? No one yet knows. Perhaps the preferred frame is a local effect that arises only near black hole horizons—in which case relativity continues to apply in general. On the other hand, perhaps the preferred frame exists everywhere, not just near black holes—in which case relativity is merely an approximation to a deeper theory of nature. Experimenters have yet to see such a frame, but the null result may simply be for want of sufficient precision.

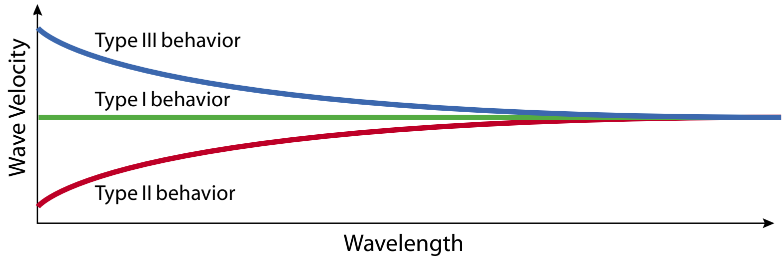
Physicists have long suspected that reconciling general relativity with quantum mechanics would involve a short-distance cutoff, probably related to the Planck scale. The acoustic analogy bolsters this suspicion. Spacetime must be somehow granular to tame the dubious infinite redshift.

If so, the analogy between sound and light propagation would be even better than Unruh originally thought. The unification of general relativity and quantum mechanics may lead us to abandon the idealization of continuous space and time and to discover the "atoms" of spacetime. Einstein may have had similar thoughts when he wrote to his close friend Michele Besso in 1954, the year before his death: "I consider it quite possible that physics cannot be based on the field concept, that is, on continuous structures." But this would knock out the very foundation from under physics, and at present scientists have no clear candidate for a substitute. Indeed, Einstein went on to say in his next sentence, "Then *nothing* remains of my entire castle in the air, including the theory of gravitation, but also nothing of the rest of modern physics."

Fifty years later the castle remains intact, although its future is unclear. Black holes and their acoustic analogues have perhaps begun to light the path and sound out the way. SA

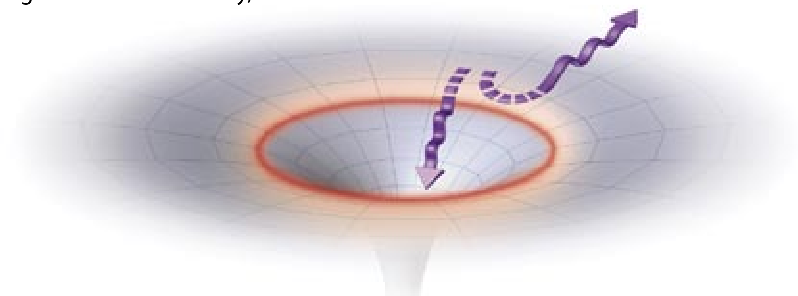
Hawking Was Right, but ...

The fluid analogies suggest how to fix Hawking's analysis. In an idealized fluid, the speed of sound is the same no matter the wavelength (so-called type I behavior). In a real fluid, the speed of sound either decreases (type II) or increases (type III) as the wavelength approaches the distance between molecules.



Hawking's analysis is based on standard relativity theory, in which light travels at a constant speed—type I behavior. If its speed varied with wavelength, as in the fluid analogues, the paths of the Hawking photons would change.

For type II, the photons originate outside the horizon and fall inward. One undergoes a shift of velocity, reverses course and flies out.



For type III, the photons originate inside the horizon. One accelerates past the usual speed of light, allowing it to escape.

Because the photons do not originate exactly at the horizon, they do not become infinitely redshifted. This fix to Hawking's analysis has a price: relativity theory must be modified. Contrary to Einstein's assumptions, spacetime must act like a fluid consisting of some unknown kind of "molecules."

GEORGE RETSECK

MORE TO EXPLORE

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