Black Holes Can Dance

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Abstract

This is the story of black holes seen from one astronomer's perspective. Although some very technical information is included, the intent is to review some information about this odd piece of nature.

Introduction

SIMPLY PUT, A *BLACK HOLE* [i] is a region of space from which nothing, not even light, can escape. It is the result of the deformation of space-time caused by a *very* compact mass – a lot of mass in a teeny (actually zero) volume. Around the black hole there is an undetectable surface (called the event horizon) which marks the point of no return. Once inside nothing can escape. A black hole is called "black" because it absorbs all the light that hits it, reflecting nothing, just like a perfect blackbody in thermodynamics. We cannot see, hear, smell, touch, or taste it.

Now that we know that much, let us look at some history.

Newton's universe did not include black holes. I shall start there, and assume we know the basics of Newton's laws.

Even though Newton did not discuss black holes, the idea of them has been around for some time.

The idea of a body so massive that even light could not escape was first put forward by geologist John Michell[ii] in a letter written to Henry Cavendish[iii] in 1783 to the Royal Society:[iv]

> If the semi-diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of 500 to 1, a body falling from an infinite height towards it would have acquired at its surface greater velocity than that of light, and consequently supposing light to be attracted by the same force in proportion to its *vis inertiae*, with other bodies, all light emitted from such a body would be made to return towards it by its own proper gravity.

In 1796, mathematician Pierre-Simon Laplace[v] promoted the same idea in the first and second editions of his book *Exposition du système du Monde* (it was removed from later editions). He pointed out that there could be massive stars whose gravity is so great that not even light could escape from their surface.

Such dark objects were ignored until the 20th century, since it was not understood how gravity could influence a massless wave such as light.

It took Albert Einstein (and others) to show that gravity can influence light. First with his Special Theory of Relativity and second with his General Theory of Relativity he proved that gravity does influence the motion of light. According to Einstein, space warps when close to matter. The more matter there is, the more space warps. The description of the curvature (warping) of space is the mathematically complicated part of general relativity. It involves tensor calculus and *metrics*. In mathematics, the word metric refers to a fairly general function which defines the 'distance' between elements in a set. I tend to think of a metric as a bendable and twistable ruler that allows one to measure intervals (distances) between two events. **Keep the concept of a metric in mind**.

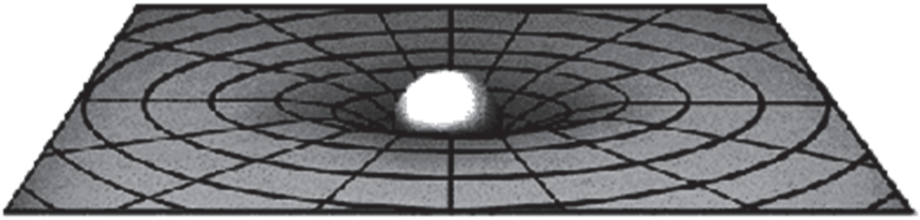


Figure 1. The curvature of space caused by a massive object.

Figure 1 represents a two-dimensional slice through three-dimensional space showing the curvature of space produced by a spherical object, *e.g.*, the Sun. Einstein's view is that the planets follow the curvature of space around the Sun (and produce a tiny amount of curvature themselves).

Metrics and the Special Theory of Relativity

The Special Theory of Relativity (STR) has as its basic premise that light moves at a uniform speed, c = 300,000 km/s, in all frames of reference. This results in setting the speed of light as the absolute speed limit in the universe and also produces the famous relationship between mass and energy, $E = mc^2$.

In Newtonian flat space (the kind we are familiar with) the metric that defines distance is:

$$ds^2 = dx^2 + dy^2 + dz^2$$

where *ds* is the distance and (*x*, *y*, *z*) are the spatial coordinates (remember your high school geometry). Strictly speaking this is the line element, not the metric. For the purpose here, I use the words interchangeably.

In STR the metric becomes a combination of time and space:

$$ds^2 = -c^2dt^2 + dx^2 + dy^2 + dz^2 .$$

In spherical coordinates it is:

$$ds^2 = -c^2dt^2 + dr^2 + r^2d\theta^2 + r^2 \sin^2 \theta d\phi^2$$

or more concisely

$$ds^2 = -c^2dt^2 + dr^2 + r^2d\Omega^2 .$$

It is from STR that we get the term *space-time* – space and time forming a single continuum, *ds*. Note the difference between this metric and the metric of Newton's world. In Einstein's world the distance (interval) between two events depends on the time *and* space intertwined.

The General Theory of Relativity

As useful as Newtonian mechanics may be, it is merely a limiting case of relativistic mechanics. The General Theory of Relativity (GTR) is the geometric theory of gravitation published by Albert Einstein in 1916. It is the current description of gravitation in modern physics.

We need GTR because **black holes require GTR for explanation**, yet GTR is a difficult subject no matter how one looks at it. This is what the basic equation of GTR looks like:

$$G_\mu^\nu + \Lambda g_\mu^\nu = \frac{8\pi G}{c^4} T_\mu^\nu$$

where G_μ^ν is the Einstein tensor,[vi] Λ is the cosmological constant,[vii] g_μ^ν is the metric tensor,[viii] and T_μ^ν is the stress-energy tensor. This equation describes the interaction of gravitation as a result of space-time being curved by matter and energy. The left side of the equation contains the information about how space is curved (the geometry), and the right side contains the information about the location and motion of the matter (the dynamics). When fully written out, the equations are a system of coupled, nonlinear, hyperbolic-elliptic partial differential equations.

You may now forget these equations because they are not necessary for the rest of the paper except to say that solutions to these equations under certain conditions give us black holes.

Two Metrics That Define Black Holes

Solutions to the Einstein's GTR equations are *metrics of space-time* – ways to describe gravity and mass interacting with each other. **The metric is the fundamental object of study for black holes**.

The first solution came in 1916 when astronomer Karl Schwarzschild (1873-1916) solved the equations for the particular case of a non-rotating spherically symmetric point mass.[ix,x] This point mass solution (where all the mass is concentrated into a single point) describes a black hole.

The metric solution for the point mass was named after Schwarzschild – the *Schwarzschild metric* defines the space-time environment near a black hole of mass *m*. The metric is spherically symmetric and non-rotating (no angular momentum). This is the simplest type of black hole. The metric only looks complicated:

$$c^2 d\tau^2 = \left(1 - \frac{2Gm}{c^2 r}\right) c^2 dt^2 - \left(1 - \frac{2Gm}{c^2 r}\right)^{-1} dr^2 - r^2 d\Omega^2 .$$

The quantity $\left(1 - \frac{2Gm}{c^2 r}\right)$ appears twice. It is there so that in the limit of large r and small m the metric reduces to the Newtonian gravitational field around a point mass. At $r = 0$ there is a true singularity.[xi] Note, however, the possibility of infinity when $r = 2Gm/c^2$. This particular value for r is called the *Schwarzschild radius* (r_s), a special radius that is quite useful, as we shall see.[xii]

It took some time for the next black hole solution to appear; however, in 1963, mathematician Roy Kerr found the exact solution for a rotating black hole. The more complicated *Kerr metric* for a black hole with angular momentum *J* is:

$$c^2 d\tau^2 = \left(1 - \frac{r_s r}{\rho^2}\right) c^2 dt^2 - \frac{\rho^2}{\Delta} dr^2 - \rho^2 d\theta^2 - \left(r^2 + \alpha^2 + \frac{r_s r \alpha^2}{\rho^2}\sin^2\theta\right)\sin^2\theta d\phi^2 + \frac{2 r_s r \alpha \sin^2\theta}{\rho^2} c dr d\phi ,$$

where r_s is the Schwarzschild radius, and the scale lengths α, ρ, and Δ are:

$$\alpha = \frac{J}{mc},$$

$$\rho^2 = r^2 + \alpha^2 \cos^2 \theta, \text{ and}$$

$$\Delta = r^2 - r_s r + \alpha^2.$$

At $r = 0$ there is the true singularity, however, the Kerr metric has two values for r where it appears to be singular: r_{inner} and r_{outer}. The inner surface occurs where the purely radial component of the metric goes to infinity:

$$r_{inner} = \frac{r_s + \sqrt{r_s^2 - 4\alpha^2}}{2}.$$

The other singularity occurs where the purely temporal component of the metric changes sign from positive to negative:

$$r_{outer} = \frac{r_s + \sqrt{r_s^2 - 4\alpha^2 \cos^2 \theta}}{2}.$$

The Kerr black hole, therefore, has two special radii with the *ergosphere* (sphere of influence of the black hole – more on it later) between them. The outer surface is also called the static limit. The inner surface is also called the event horizon.

Note something important. The parameter t (time) does not occur in the right side of either metric. **Time stops at a black hole**.

So by the 1960s scientists could describe the enivironment around stationary,[xiii] non-rotating, and rotating black holes.[xiv] Given these metrics, people got to work on the dynamics of black holes.

The Four Laws

By the 1970s research by many people led to the formation of the four laws of black hole dynamics. These laws describe the behavior of a black hole in close analogy to the laws of thermodynamics by relating mass to energy, surface area to entropy, and surface gravity to temperature. The analogy was completed when Stephen Hawking, in 1973, showed that quantum field theory predicts that black holes radiate (*Hawking radiation*, see the section on this) like a blackbody with a temperature proportional to the surface gravity of the black hole.[xv] Further description of the four laws is highly mathematical and beyond the scope of this paper.

Despite these laws we still cannot describe a black hole all the way to $r = 0$. That will require combining quantum and gravitational effects into a single theory, although the single theory does have a name: quantum gravity. This is an area of active research.

However, the four laws led to a definition of what one *can* measure in a black hole.

Black Holes Have No Hair

The four laws led to the 'no-hair theorem' – black holes have no hair. This means that a stationary black hole is completely described by only three things: its *mass*, *angular momentum*, and *electric charge*. There is no other way to 'grab' onto (measure) a black hole. These properties are special because they and only they are detectable from outside the black hole. For example, a charged black hole repels other like charges just like any other charged object. Why these three? The reason is mathematical; these are unique, conserved imprints in the external fields of the black hole (conserved Gaussian flux intervals).

Theoretically a black hole may possess electric charge but it would quickly attract charge of the opposite sign and become neutral. The net result is that any realistic black hole would tend to exhibit zero charge.

I shall discuss two types of black holes: one defined by the Schwarzschild metric and one defined by the Kerr metric. There are others, but they are quite specialized. In fact, there are four basic types:

	Non-rotating	Rotating
No charge	Schwarzschild	Kerr
Charged	Reissner-Nordström	Kerr-Newman

When most people think of a black hole, it is usually the Schwarzschild black hole. So I shall discuss this one first.

The Particulars of the Schwarzschild Black Hole

The Schwarzschild black hole is stationary (not moving through space) with zero charge and is non-rotating. It is 'dead' in the sense that one can never extract from it any of its mass-energy. No information can ever come from a Schwarzschild black hole. This means it is stable against a perturbation (*e.g.*, a kick), were you so inclined.

At the Schwarzschild radius, r_s, some of the terms in the metric apparently become infinite. This is not a true singularity.[xvi] It is due to the choice of spherical coordinates; however, it does have a physical effect.

In 1958 physicist David Finkelstein[xvii] identified the Schwarzschild surface $r_s = 2Gm/c^2$ as an *event horizon*, "a perfect unidirectional membrane: causal influences can cross it in only one direction." That means it is a one way gate. Things go in and do not come out. At the rim of the event horizon one must travel at the speed of light just to stay in place. Once inside the event horizon the radial coordinate 'evaporates' because there can be *no* spatial direction that will lead back to the outside. **Once inside the event horizon escape is not possible**.

The 'size' of a black hole, as determined by the radius of its event horizon (Schwarzschild radius), is roughly proportional to its mass M:

$$r_s = \frac{2GM}{c^2} \approx 2.95 \frac{M}{M_\odot} \text{km},$$

where $M_\odot$ is the mass of the Sun. This relation is exact only for Schwarzschild black holes; for more general black holes it can differ up to a factor of two. Table I shows this relation for some common objects.

Table I. The Schwarzschild radius for different sized objects.

Object	$r_{\text{Schwarzschild}}$
Earth	1 cm
Jupiter	3 meters
Sun	3 kilometers
3 solar-mass star	9 kilometers
3000 solar masses	9000 kilometers

So, for the Earth to become a black hole, all its mass must be consolidated within a sphere of a one centimeter radius. This is highly unlikely.

Figure 2 illustrates how space-time curves about a Schwarzschild black hole. At the center of a black hole lies a true gravitational singularity.[xviii] At $r = 0$ the space-time curvature becomes infinite. For a non-rotating black hole this region takes the shape of a single point. For a rotating (Kerr) black hole it is smeared out to form a ring singularity lying in the plane of rotation. In both cases the singular region has zero volume. The singular region can thus be thought of as having infinite density. All this really means is that we do not understand what happens at the singularity.

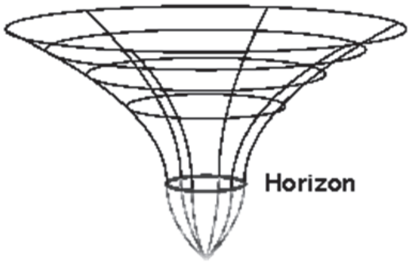


Figure 2. Curved space-time around a Schwarzschild black hole.

Does this mean that gravity is somehow different around a black hole? It is misleading to say that black holes have 'stronger' gravity than other masses. Black hole or not, the curvature one feels depends strictly on the mass of the object and the distance one is from that mass, not whether the object is a black hole. When that mass is concentrated in a small volume, however, one can get closer to the mass than otherwise is the case. This may be why one thinks gravity is stronger around a black hole. It is actually the field density that is greater. The gravitational field density close to an Earth mass compressed within a 1 cm radius is much higher than the density around an Earth mass with its current radius. A lot of mass in a very tiny space can strongly warp the space nearby – tiny and nearby being the key words.

So, if the Sun became a black hole, would we on Earth notice? We would miss the sunlight and die (so we would notice), but the gravitational effect on Earth would be what it always was. The mass of the Sun has not changed (even though it occupies a smaller volume); the Earth's distance from the Sun has not changed; therefore, the Earth feels the same effect and continues to orbit the black hole Sun.

This leads me to the next point.

Black holes are *not* cosmic vacuum cleaners. They do not zoom around space sucking up matter. The black hole Sun will not scoop up the Earth. Far from the Sun there is no unusual gravitational influence. Only within a few Schwarzschild radii is there a significant effect. Black holes *can* accrete matter but only when the matter is quite close. In fact, scientists believe black holes are surrounded by *accretion disks* – a disk of accreting matter (usually gaseous) orbiting the central object.

Now that we know a bit more about them, let us see how they are made.

Making a Black Hole

There are two classes of black holes: (1) a stellar mass black hole, and (2) a super massive black hole.

Class (1) happens when a heavyweight star reaches the end of its life. One way to classify stars is by their birth weight. Heavyweight stars are born with more than 30 solar masses to their credit. Most of a star's life is spent maintaining a balance between two forces: radiation pressure from the nuclear fusion in the core that pushes outward; and the gravitational force trying to compress the gas inward. Ultimately a heavyweight star will, as all stars do, consume all its nuclear fuel. It can then no longer support itself against a subsequent gravitational collapse. If it fails to eject its excess mass in the collapse process then nothing can stop the stellar remnant from collapsing toward a point – forming a black hole. This collapse happens in milliseconds – the star winks out. Our Sun (a lightweight star) is not massive enough to end its life this way. It will end as a white dwarf. A middleweight star (between 6 and 30 solar masses) will explode as a supernova and end as a neutron star.

Most stars are not perfectly spherical and have a lot of angular momentum, so the gravitational collapse produces a black hole more in line with a Kerr black hole than a Schwarzschild black hole.

Class (2) is thought to lurk in the centers of most galaxies. A super massive black hole contains thousands to millions of solar masses. Once a super massive black hole has formed, it can continue to grow by absorbing additional matter. One model for the formation of super massive black holes is by slow accretion of matter onto a stellar mass black hole. Another model involves a large gas cloud collapsing into a relativistic star of perhaps a hundred thousand solar masses or larger. The star would then become unstable and may collapse directly into a black hole without a supernova explosion. Super massive black holes have properties which distinguish them from stellar mass black holes:

- The average density of a super massive black hole (defined as the mass divided by the volume within its Schwarzschild radius) can be as low as the density of water for very high mass black holes.
- The tidal forces in the vicinity of the event horizon are significantly weaker than the tidal forces around a stellar mass black hole.

Astronomers think the universe is littered with black holes, that they are not rare at all. In addition to the stellar type they think that nearly every galaxy has a central super massive black hole. What if we could visit one?

A Trip to a Black Hole

An observer falling into a Schwarzschild black hole cannot avoid the singularity at $r = 0$. Any attempt to do so will only shorten the time taken to get there. As the traveler spirals in, there is a last stable orbit[xix] at a distance of $3r_S$. Continuing inward, the traveler crosses the event horizon. At the singularity the traveler is crushed to infinite density and its mass added to the black hole. Before that happens, though, it will have been torn apart by the tidal forces in a process sometimes referred to as *spaghettification* (I did not make that up) or the *tube-of-toothpaste-effect*.

To describe this in more detail, assume there are two astronauts, a smart one and a dumb one. Their spaceship arrives near a 3 solar mass black hole ($r_S = 9$ km). The smart astronaut stays in the spaceship. The dumb astronaut jumps toward the black hole. Let us pick up the action 900 km away ($100r_s$).

At this distance of 100 r_S from the black hole the dumb astronaut is torn apart due to the tidal effect of gravity, and the story ends. For comparison, the gravity tide on a human (head to toe) on the Earth's surface is about one millionth of a *g*.

For a 3 solar mass black hole the tidal force of the black hole is shown in Table II. Remember that tidal forces go as $1/r^3$, so the tides quickly become fatal as one approaches the black hole.

Table II. Tidal force in *g*'s versus distance in km from a 3 solar mass black hole.

Distance (km)	Force (g's)
6400	0.5
2000	18
1000	144
100	150,000
10	150,000,000

For the purposes of argument, though, assume the dumb astronaut is 'stretchable.' Then as he falls, toe first, his toes are closer to the upcoming event horizon than his head. The gravity tides between his toes and head cause his toes to travel faster than his head. He stretches. The closer he gets, the more he stretches. Simultaneously he is squeezed into regions of ever decreasing circumference. He gets longer and thinner, forming dumb astronaut spaghetti strings.

As he travels toward the event horizon he may notice nothing out of the ordinary, except an inability to steer himself in any but one direction – which is toward the "invisible" hole. He will never know when he has crossed the event horizon were it not for the increased tidal tugging that draws his body longer and longer, squeezing in from the sides (actually at this point he is a set of disconnected atoms, zooming along all in a line). Just before he reaches the event horizon, each piece of him emits high energy radiation (x-rays) as that piece disappears forever. He winks out of sight with a puff of radiation. It is a rather spectacular way to die.

And it is a wonderful way to garner energy. The efficiency of energy generation near a stationary black hole is about 6%. Near a rotating black hole this reaches about 30% efficiency. This is a staggering amount. It is the best return of energy known. Compare the efficiency of combustion on Earth which is only about 10^{-8}. The efficiency of nuclear burning (in a star) is about 7×10^{-3}.

A visit to a super massive black hole is less dramatic although it ends the same way. If the mass of the black hole is about 30,000 solar masses then the dumb astronaut will not be torn apart by tidal forces at the event horizon. This will wait until he is much deeper inside. Of course, once he crosses the event horizon he cannot return or send messages. Although he may survive those tidal forces, the high energy radiation (all those x-rays and gamma rays lurking at the event horizon) will fry him.

One can calculate how long the dumb astronaut spaghetti string will "live" once inside the event horizon. No matter how he approaches a black hole of mass M, once inside the event horizon he will be killed at the $r = 0$ singularity in a proper time of about $1.54 \times 10^{-5}\ M/M_\odot$ seconds. So for a 10 solar mass black hole, he will die in 154×10^{-5} sec (0.00154 sec). One way or another, **the dumb astronaut will not survive the trip**.

Time Dilation

If the dumb astronaut carries a flashlight and points it back at the smart astronaut, and flashes it in a regular pattern, what will the smart astronaut see? She will see the flashes get further and further apart eventually slowing down to a stop (after an infinite amount of time). The GTR predicts that time will slow in the presence of matter – this is called time dilation. It is not just clocks by the way, all physical processes, including clocks ticking (however they measure their ticks), hearts beating, aging, *etc*., must slow down, but the only one who notices is the distant timekeeper. This is not an imaginary effect. When transporting atomic clocks on the Earth, one must correct for the GTR effects of the Earth on the moving clock.

Gravitational Redshift

In addition to the slow down of time, the light she sees is redshifted more and more as the dumb astronaut gets closer to the event horizon. This is not a Doppler shift. Light loses energy when escaping from a gravitational field. Because the energy of light is proportional to its frequency, a shift toward lower energy represents a shift toward the red for visible light. This gravitational redshift was first observed in the spectra of dense white dwarf stars, whose light is redshifted by about 1Å. Gravitational redshift was experimentally verified on Earth by the Pound–Rebka experiment of 1959.

Now that we know the dumb astronaut will not survive, is there a way we can we tell that he fell in?

Cosmic Censorship

When an object falls into a black hole, any and all information about the shape of the object or distribution of charge on it is evenly distributed along the horizon of the black hole, and is lost to outside observers. So not only does the dumb astronaut disintegrate, but also there is no way to determine that it was a dumb astronaut that fell in.

Because the black hole eventually achieves a stable state with only three measureable parameters (mass, charge, and angular momentum), there is no way to avoid losing information about the initial conditions. Nature puts a curtain around black holes so that we cannot see inside or know what happens inside – this cosmic censorship is complete. **There are no ‘naked’ singularities**. And the event horizon must be real, not complex.[xx] The information that is lost includes every quantity, including the total baryon number, lepton number, and all the other nearly conserved pseudo-charges of particle physics.

At least that was the state of the current thought until the 1970s. The physicist Stephen Hawking (author of *A Brief History of Time* and *The Universe in a Nutshell*) has long worked in theoretical cosmology. In 2009 he received the Presidential Medal of Freedom. He even played himself on *Star Trek*. I discuss one aspect of his work next.

Hawking Radiation

In 1974 Stephen Hawking realized that black holes are not absolutely black. There are quantum effects that allow black holes to emit blackbody radiation. The temperature of this radiation is inversely proportional to the black hole's mass; the tinier the black hole the higher the temperature of the radiation – called *Hawking radiation*.

Hawking radiation is due to particle/anti-particle pairs (*e.g.*, electron/positron) which are continuously created and annihilated in free space. When this pair creation happens near a black hole it is possible for one of the two particles to cross the event horizon before it meets and annihilates its partner. The other particle is then free to leave the scene, making the black hole appear to the outside world as a source of radiation. In other words, there is 'new' energy. So to satisfy energy conservation, the particle that fell in must have a negative energy (with respect to an observer far away from the black hole). Thus, the black hole loses mass, and, to an outside observer, it appears that the black hole has just emitted a particle. It takes energy to create new particles. This energy must come from the black hole. The black hole therefore decreases its mass as it radiates. Thus black holes will slowly evaporate.

A one solar mass black hole has a temperature of only 60 nanoKelvin (v-e-r-y cold); in fact, such a black hole would absorb far more cosmic microwave background radiation than it emits. Evaporation will take 10^{70} years. This is far longer than the age of the universe.

A smaller black hole of 4.5×10^{22} kg (about the mass of the Moon) would be in equilibrium at 2.7 K, absorbing as much radiation as it emits. Even smaller black holes would emit more than they absorb, and thereby lose mass.

For a miniature black hole – about 10^{12} kg mass which is the mass of a mountain – evaporation will take about as long as the universe is old. It is conceivable that conditions in the very earliest epochs of the universe might have been just right to compress pockets of matter into these miniature black holes. The Schwarzschild radius of such a black hole is about 10^{-15} m, comparable to the size of a subatomic particle. This begs the question how these teeny black holes got formed; however, at the end of its life, the mass of the tiny black hole becomes smaller and smaller, and hence its temperature tends towards infinity. The black hole ultimately disappears in an explosion. Fortunately (or unfortunately) current physics is unable to explain the last phases of the evaporation of the black hole.

Black Hole in a Bathtub

Recently scientists in Canada have measured the equivalent of Hawking radiation from a "bathtub black hole." In August 2010, the Canadian scientists announced[xxi] that they had made an event horizon in a water channel. They sent a steady flow of water in one direction. As it passed over the top of a piece of wood whittled in the shape of an airplane wing, the water traveled faster (aka Bernoulli). In the opposite direction, the group created water waves. When these waves approached the wing, where water was flowing faster, they slowed to a stop. Technically this bathtub version is a white hole, an inverted black hole that keeps waves out rather than bringing them in. But the white hole serves as an analog because it shares an important feature with astrophysical black holes — an imaginary boundary that emits an unusual kind of radiation. These laboratory emitters of Hawking type radiation share one required feature with their astrophysical counterparts — a point of no return, analogous to the black hole's event horizon. Both types have event horizons, so both ought to emit Hawking radiation. In fact, pairs of short-wavelength waves were created at the bathtub horizon and swept away, and the energy of these emitted waves matches what would be predicted from Hawking radiation around a real black hole.

This seems a bit forced to me.

Hawking radiation introduced a debate in cosmological circles. Is it consistent with the no hair theorem? This leads to a paradox.

The Paradox in Hawking Radiation

There is a paradox with Hawking radiation. From the no hair theorem, one expects the Hawking radiation to be completely independent of the material entering the black hole. All information is lost entering a black hole. Nevertheless, if the material entering the black hole were a pure quantum state, the transformation of that state into the mixed state of Hawking radiation would destroy information about the original quantum state. The rules of quantum mechanics say information is conserved in the wave function. The no hair theorem says the information is lost – a physical paradox.

Hawking remained convinced that the equations of black hole thermodynamics together with the *no-hair theorem* led to the conclusion that quantum information will be destroyed. This annoyed many physicists, notably John Preskill, who in 1997 bet Hawking and Kip Thorne that information was not lost in black holes. This led to the

Susskind-Hawking battle, where Leonard Susskind and Gerard't Hooft publicly declared war on Hawking's solution, with Susskind publishing a popular book about the debate in 2008 (*The Black Hole War: My battle with Stephen Hawking to make the world safe for quantum mechanics*). The book carefully notes that the war was purely a scientific one, and that at a personal level, the participants remained friends. The solution to the problem is the holographic principle (a property of quantum gravity combined with string theory). With this, as the title of an article puts it, "Susskind quashes Hawking in quarrel over quantum quandary."

In July 2005, Stephen Hawking announced a theory that quantum perturbations of the event horizon could allow information to escape from a black hole, which would resolve the information paradox. When announcing his result, Hawking also conceded the 1997 bet, paying Preskill with a baseball encyclopedia "from which information can be retrieved at will." However, Thorne remains unconvinced of Hawking's proof and declined to contribute to the award.

It does not end there. Roger Penrose advocates the Conformal Cyclic Cosmology (CCC) which critically depends on the condition that information is in fact lost in black holes. In CCC, the universe iterates through infinite cycles, with the future time-like infinity of each previous iteration being identified with the Big Bang singularity of the next. This CCC model might in future be tested experimentally by detailed analysis of the cosmic microwave background radiation (CMB): if true the CMB should exhibit circular patterns with slightly lower or slightly higher temperatures. In November 2010, R. Penrose and V. G. Gurzadyan announced they had found evidence of such circular patterns (Figure 3), in data from the Wilkinson Microwave Anisotropy Probe corroborated by data from the BOOMERanG experiment[xxii]. However, the statistical significance of the claimed detection has been questioned. Three groups have independently attempted to reproduce these results, and found that the detection of the concentric anomalies was not statistically significant. Stay tuned.

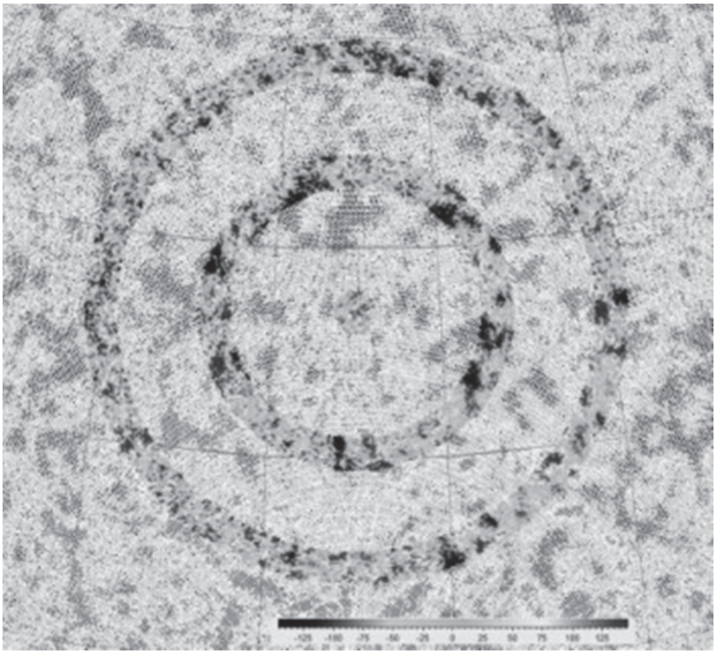


Figure 3. Possible circles in BOOMERanG data – the concentric circles are highlighted. The mottling represents the wrinkles in space-time of the cosmic microwave background.

The Particulars of the Kerr Black Hole

The other type of black hole I shall discuss is the Kerr black hole, which rotates (has angular momentum). Seen in cross-section, the Kerr black hole is oval-shaped, with the ergosphere extending farther into space at the black hole's equator than at its poles (Figure 4). The $r = 0$ singularity is a ring of zero volume.

The Kerr black hole is actually more significant than the Schwarzschild black hole because most black holes spin. Part of the mass is actually stored as rotational energy in the ergosphere (which means 'place where work can be done') and is, in theory, available for extraction since the mass has not yet crossed the event horizon. This type can inject energy into its surroundings – hence this type is 'live.'

Kerr space-time is what happens when a black hole has reached its final evolutionary state. Kerr space-time is time-independent, meaning that nothing in Kerr space-time changes over time. In effect, time stands still. Remember that the time parameter t does not appear in the right side of the Kerr metric. A black hole in such a state is essentially stationary.

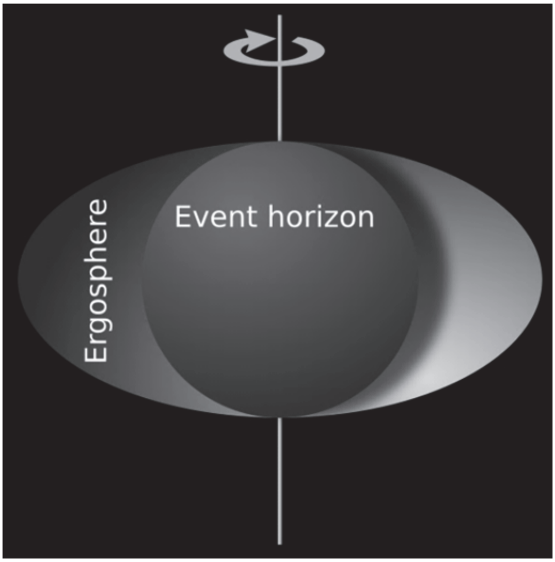


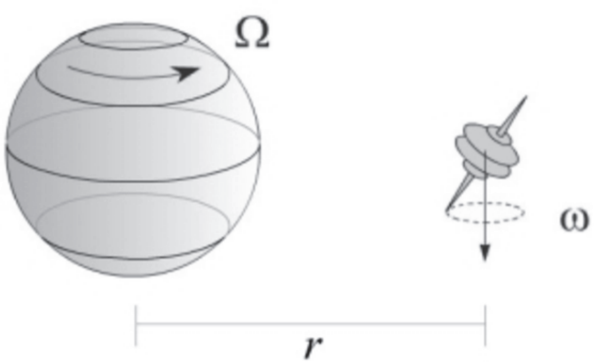
Figure 4. Side view of a conceptual Kerr black hole.

Frame Dragging

When the black hole is spinning it actually pulls the fabric of space-time around with it – an effect called frame dragging, also known as the *Lense-Thirring* effect. The rotation of the black hole or even the rotation of a very massive object will alter local space-time by dragging a nearby object out of position compared with the predictions of Newtonian physics. Frame dragging is like what happens if a bowling ball spins in a thick fluid such as molasses. As the ball spins, it pulls the molasses around itself. Anything stuck in the molasses will also move around the ball. This dragging happens in the ergosphere. The closer to the black hole the greater the dragging.

Inside the ergosphere (inside the static limit) nothing can stand still; therefore, particles falling within the ergosphere are forced to rotate and thereby gain energy. They *must* orbit in the same direction as the black hole rotates. So long as they are still outside the event horizon, they may, however, escape the black hole. The net process is that the rotating black hole emits energetic particles at the cost of its own total energy. The possibility of extracting spin energy from a rotating black hole was first proposed by the mathematician Roger Penrose in 1969.

The Earth is a very massive object; therefore, as the Earth rotates, it pulls space-time in its vicinity around itself. This action introduces a precession on all gyroscopes in a stationary system surrounding the Earth (Figure 5). The predicted Lense-Thirring effect is small — about one part in a few trillion – yet measureable. A Foucault pendulum would have to oscillate for more than 16000 years to precess 1 degree.



$$\frac{\omega}{\Omega} = \frac{2}{3}\frac{r_s}{r}$$

Figure 5. The Earth rotating with angular velocity Ω; The gyroscope a distance *r* away precesses with angular velocity ω.

LAGEOS (Laser Geodynamics Satellites) are a series of scientific research satellites designed to provide an orbiting laser ranging benchmark for geodynamical studies of the Earth. The Lense-Thirring effect on LAGEOS due to the rotating Earth has been measured. The effect shifts the orbits of the satellites about 2 meters per year in the direction of rotation. The results are compatible with the predictions of GTR.

Another test of frame dragging is the Gravity Probe B satellite – launched in 2004 (now decommissioned) with a dual purpose: to measure the frame dragging of Earth, and to measure the geodetic effect – the amount by which the Earth warps the local space-time in which it resides. For Gravity Probe B, in polar orbit 642 km above the Earth, frame dragging causes its gyroscope spin axes to precess in the east-west direction by a mere 39 milliarcsec/yr. — an angle so tiny that it is equivalent to the average angular width of Pluto as seen from Earth.

Initial results from Gravity Probe B confirmed the expected geodetic effect to an accuracy of about 1%. In December 2008 NASA reported that the geodetic effect was confirmed to better than 0.5%. Unfortunately the expected frame-dragging effect was similar in magnitude to the noise level. Work continues on the data to model and account for these sources of unintended signal, thus permitting extraction of the frame-dragging signal if it exists at the expected level. By August 2008 the uncertainty in the frame-dragging signal had been reduced to 15%. Final results are expected in 2011.

Many astrophysical objects, *e.g*. pulsars and black holes, emit jets of energy. These jets may also provide evidence for frame-dragging. Such jets are extremely powerful bursts of energy. Some of them extend huge distances into space. There are images of jets later in the paper (Figures 12, 13). These jets are tightly collimated flows of energy, collimated perhaps by the twisting of magnetic field lines by frame dragging.

The energy released in an astrophysical jet is overwhelmingly powerful – at the highest end of the electromagnetic spectrum – x-rays and gamma rays. A trip through a jet would quickly fry the traveler. Or is there a way to cut through space-time?

Shortcuts through Space – Wormholes?

If one can avoid the jet, perhaps one can escape to another universe. A wormhole is a hypothetical topological feature of space-time that would be, fundamentally, a "shortcut" through space-time. The physicist John Wheeler coined the term *wormhole* in 1957; however, in 1921, the mathematician Hermann Weyl already had proposed the wormhole theory.

There is no observational evidence for wormholes, but there are valid theoretical solutions to the equations of GTR which contain wormholes. These solutions say that it is theoretically possible to avoid the singularity at $r = 0$ and exit the black hole into a different space-time with the black hole acting as a wormhole.

For a simple explanation of a wormhole, consider space-time as a two-dimensional (2D) surface. If this surface is folded along a third dimension, it allows one to picture a wormhole "bridge." (Please note that this is merely a visualization to convey a structure existing in four or more dimensions). The parts of the wormhole could be higher-dimensional analogues for the parts of the curved 2D surface; for example, instead of mouths which are circular holes in a 2D plane, a real wormhole's mouths could be spheres in 3D space. A wormhole is, in theory, much like a tunnel with two ends each at separate points in space-time. Figure 6 illustrates a 2D wormhole.

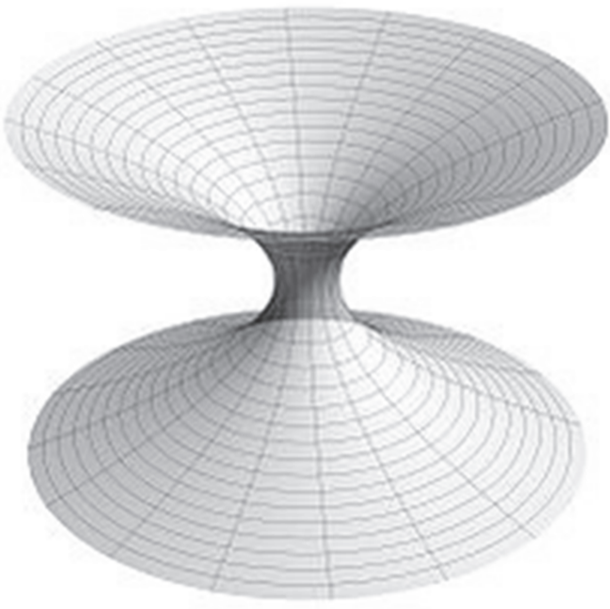


Figure 6. A 2D representation of a wormhole.

The first type of wormhole solution discovered was the *Schwarzschild wormhole*. Technically the Schwarzschild metric has a negative square root as well as a positive square root solution for the geometry. The complete Schwarzschild geometry consists of a black hole, a white hole, and two universes connected at their event horizons by a wormhole. The negative square root solution inside the horizon represents a white hole. A white hole is a black hole running backwards in time. Just as black holes swallow things irretrievably, so also do white holes spit them out.[xxiii] The negative square root solution outside the event horizon represents another universe. The wormhole joining the two separate universes is known as the Einstein-Rosen bridge. Unfortunately it is impossible for a traveller to pass through this wormhole from one universe into the other. A traveller can pass through an event horizon only in one direction. First, the traveller must wait until the two white holes have merged, and their horizons meet. The traveller may then enter through one horizon. But having entered, the traveller cannot exit, either through that horizon or through the horizon on the other side. The fate of the traveller who ventures in is to die at the singularity which forms from the collapse of the wormhole.

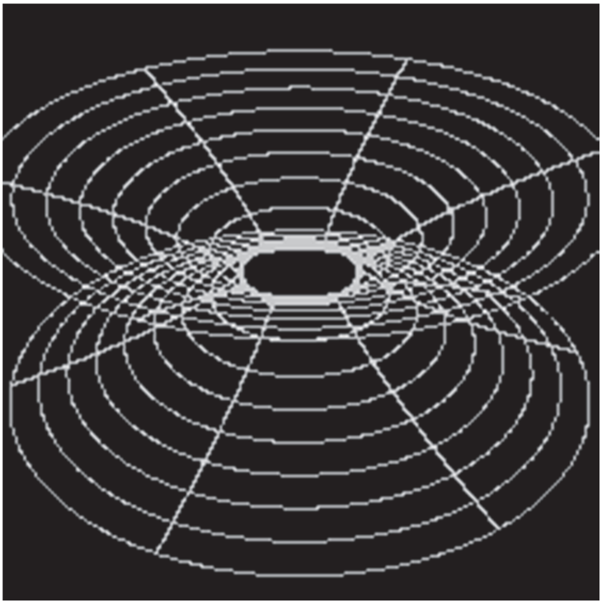


Figure 7. A 2D representation of a traversable wormhole.

Wormholes which could actually be crossed (Figure 7), known as *traversable wormholes*, would only be possible if exotic matter with negative energy density could be used to stabilize them (keep them from collapsing). Physicists have not found any natural process which would form a stable wormhole, although the quantum foam hypothesis (QFH) is sometimes used to suggest that tiny wormholes might appear and disappear spontaneously at the tiniest scale. Qualitatively QFH is described as subatomic space-time turbulence at extremely small distances of the order 10^{-35} meters. At such small scales of time and space the Heisenberg uncertainty principle allows particles and energy to come briefly into existence, and then annihilate, without violating conservation laws. However, without a theory of quantum gravity it is impossible to be certain what space-time would look like at these scales.

Finally, even if wormholes exist and are stable, they are quite unpleasant to travel through. Radiation that pours into the wormhole (from nearby stars, the cosmic microwave background, jets, *etc*.) gets blueshifted to very high frequencies, well into the high energy end of the spectrum. As you try to pass through the wormhole, you will get fried by these x-rays and gamma rays. So, at the moment, **space travel using wormholes is not possible.**

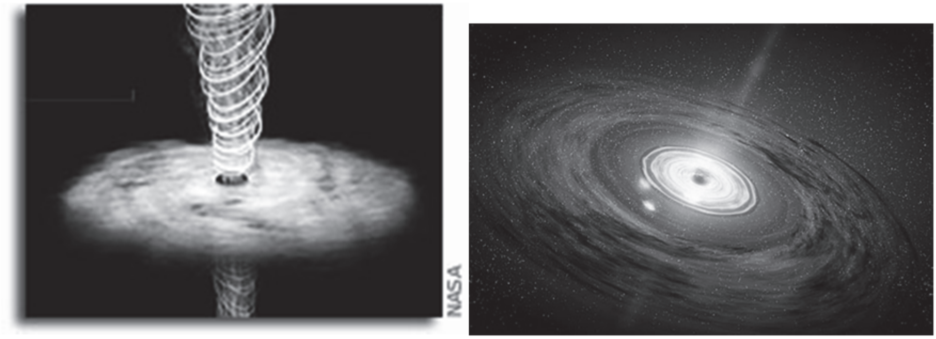


Figure 8. Two artists' conception of a black hole surrounded by an accretion disk and bipolar jets.

Observational Evidence for Black Holes

All this fancy theory means little unless there is observational evidence. Fortunately, despite its invisible interior, a black hole can be detected through its interaction with other matter.

There are several types of interactions. Five of them are: (1) A black hole exerts gravitational pull on surrounding matter, although this is indistinguishable at $r >> r_s$, from the pull of an object with the same mass; (2) Gas surrounding a black hole is pulled inward and heated so that it emits x-rays and gamma rays that might be observed; (3) A lump of matter falling into a black hole should emit a burst of gravitational waves; (4) Tidal forces will tear matter apart and eject a blob of relativistic matter (tube-of-toothpaste effect); (5) Frame dragging will twist the magnetic field lines that may surround a black hole and thus 'shake' the external plasma.

Figure 8 gives two artists' conception of a black hole surrounded by an accretion disk with two polar jets. Conservation of angular momentum means gas falling into the gravitational well created by a massive object will typically spiral in to form a Frisbee-like structure (accretion disk) around the object. **Accretion disks are where the action is.** In the case of black holes, the accretion disk is outside the event horizon. The gas in the inner regions (closer to the event horizon) becomes so hot that it will emit vast amounts of radiation (mainly x-rays), which may be detected by telescopes. In many cases, accretion discs are accompanied by relativistic jets emitted along the poles, which carry away much of the energy. The mechanism for the creation of these jets currently is not well understood, although frame dragging is part of the solution.

It is unlikely we can observe an accretion disk directly (they are too small), but the jets are easily seen (there are examples later in the paper).

The strongest evidence for black holes comes from binary star systems in which a visible star orbits a massive but unseen companion. Binary x-ray sources[xxiv] are excellent candidates for black holes because matter from the accretion disk streaming into the black hole is ionized and greatly accelerated, producing x-rays.

In 1972 an x-ray source (named Cygnus X-1) was discovered in the constellation Cygnus. The Cyg X-1 system has a blue supergiant star (HDE226868), about 25 times the mass of the sun, orbiting the x-ray source. So something non-luminous is there (neutron star or black hole). Figure 9 is an artist's conception of the Cyg X-1 system. The indirect evidence for the black hole Cyg X-1 is a good example of the search for black holes.

Doppler studies of the blue supergiant indicate a revolution period of 5.6 days about the dark object. Using that period plus spectral measurements of the visible companion's orbital speed leads to a calculated total system mass of about 35 solar masses.[xxv] The calculated mass of the dark object then is 8 to 10 solar masses; much too massive to be a neutron star which has an upper limit of about 3 solar masses – hence black hole. Figure 10 is an image of the system. The jet is clearly seen.

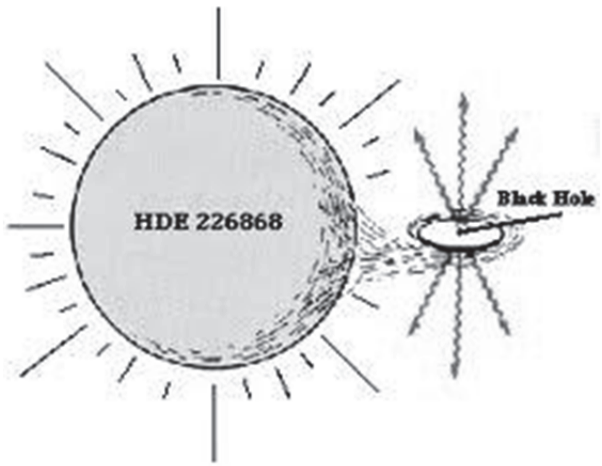


Figure 9. Artist's conception of Cygnus X-1 – matter is drawn from the supergiant star into an accretion disk around the black hole.

Further evidence for a black hole is the emission of x-rays from its location, an indication of temperatures in the millions of degrees. This x-ray source exhibits rapid variations, with time scales on the order of a millisecond. The light travel time is then a light-millisecond. This suggests a source not larger than a light-millisecond (300 km), so it is very compact. The only possibility that would place that much matter in such a small volume is a black hole.

Figure 10. Jet in Cyg X-1, the jet is coming out from the center toward 1 o'clock. The accretion disk is much too small to see.

In November 2010 evidence of the youngest black hole (all of 30 years old) known to exist in our cosmic neighborhood was found. This object provides a unique opportunity to watch a black hole develop from near infancy. The object is a remnant of supernova 1979C, a supernova in the galaxy M100 approximately 50 million light years from Earth. The scientists think the progenitor star for the supernova was a star about 20 times more massive than the Sun.

Astronomers have identified numerous stellar black hole candidates, and have also found evidence of super massive black holes at the center of galaxies. In 1998, astronomers found compelling evidence that a super massive black hole is located near the Sagittarius A* region (a bright and very compact astronomical radio source discovered in 1974 at the center of our own Milky Way). Astronomers monitored the orbits of individual stars very near the black hole and used Kepler's laws to infer the enclosed mass. Recent results indicate that the super massive black hole is 4.31 ± 0.38 million solar masses. Ultimately, what is seen is not the black hole itself, but observations that are consistent only if there is a black hole present near Sgr A.* There is a nice time lapse movie of the stellar motions in the area: http://apod.nasa.gov/apod/ap001220.html.

Super massive black holes can produce amazing jets. Figure 11 shows three jets from the object 3C 75 (object number 75 in the Third Cambridge Catalogue of radio sources).

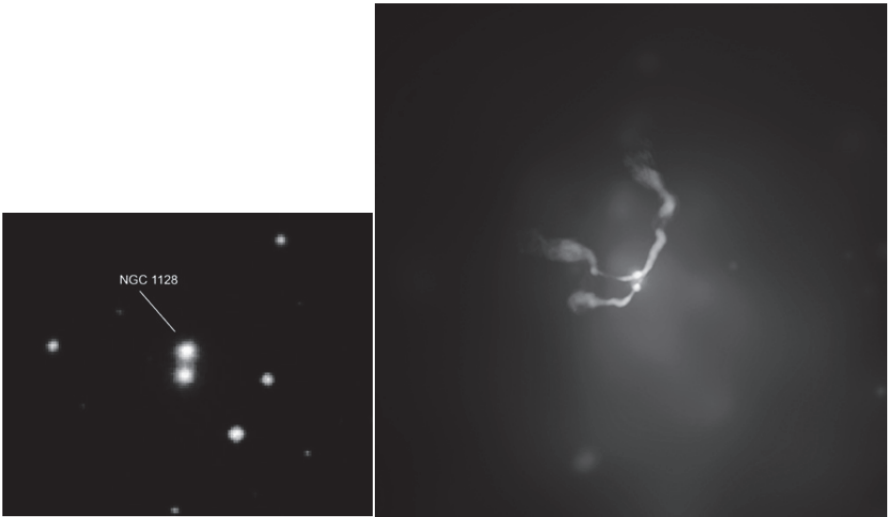


Figure 11. The right image is of 3C 75 – there are three clear jets. They originate at the bright spot in the center. The jets flare and bend as they encounter the intergalactic medium. The left image is an optical image of the galaxy NGC 1128 – the central bright dots in the right image.

The jets emanate from the vicinity of two super massive black holes (coming from the bright spot in the right image). These black holes are in the dumbbell galaxy NGC 1128, which has produced the giant radio source, 3C 75. The jets can reach incredible lengths – megaparsecs[xxvi] – streaming into intergalactic space.

The peculiar dumbbell structure of this galaxy is thought to be due to two large galaxies that are in the process of merging. Such mergers are common in the relatively congested environment of galaxy clusters. An alternative hypothesis is that the apparent structure is the result of a coincidence in time when the two galaxies are passing one another, like ships in the cosmic sea.

There is more. Black holes can come in pairs! Galaxies commonly collide and merge to form new, more massive galaxies. A merger between two galaxies should bring two super massive black holes to the new, more massive galaxy formed from the merger. The two black holes gradually spiral towards the center of this new galaxy, engaging in a gravitational tug-of-war with the surrounding stars. The result is a black hole dance.

Astronomers expect many such waltzing super massive black holes in the universe, but until recently only a handful had been found. In January of 2010, astronomers announced the discovery of 33 pairs of waltzing black holes in galaxies. This result shows that super massive black hole pairs are more common than previously known from observations. Also, the black hole pairs can be used to estimate how often galaxies merge with each other.

The largest known black hole inhabits the core of M87, a giant elliptical galaxy in the constellation Virgo. The M87 black hole appears to be about $(6.4 \pm 0.5) \times 10^9$ solar masses, with an event horizon diameter of about 18 billion km – almost twice the diameter of the orbit of Pluto. Figure 12 contains a series of photos of M87 with its jet. Surrounding the black hole is a rotating disk of ionized gas that is oriented roughly perpendicular to the jet. This gas is moving at velocities of up to roughly 1,000 km/s. Gas is accreting onto the black hole at an estimated rate equal to the mass of the Sun every ten years.

Conclusion

Black holes retain their fascination despite the decades of solid research. They are both simple and complex: simple because it takes only three parameters to describe them; complex because it takes GTR to handle the dynamics. They come singly, in binary systems, and in pairs, but never 'naked'. They come both small and large in mass. They are impossible to see, but their effects on their environment can be distinctive, although they are not cosmic vacuum cleaners. We think they are found in the centers of most galaxies. There are dozens of possible detections of stellar mass black holes.

Gravity trumps all the other forces of nature in these objects. It compresses the mass of a dozen Suns, or a million, or a billion into a pinpoint of infinite density. Space and time are squeezed out of existence, and the structure of the universe turns into a "quantum foam" that's ruled by laws that scientists do not yet fully comprehend. We have a lot more to learn.

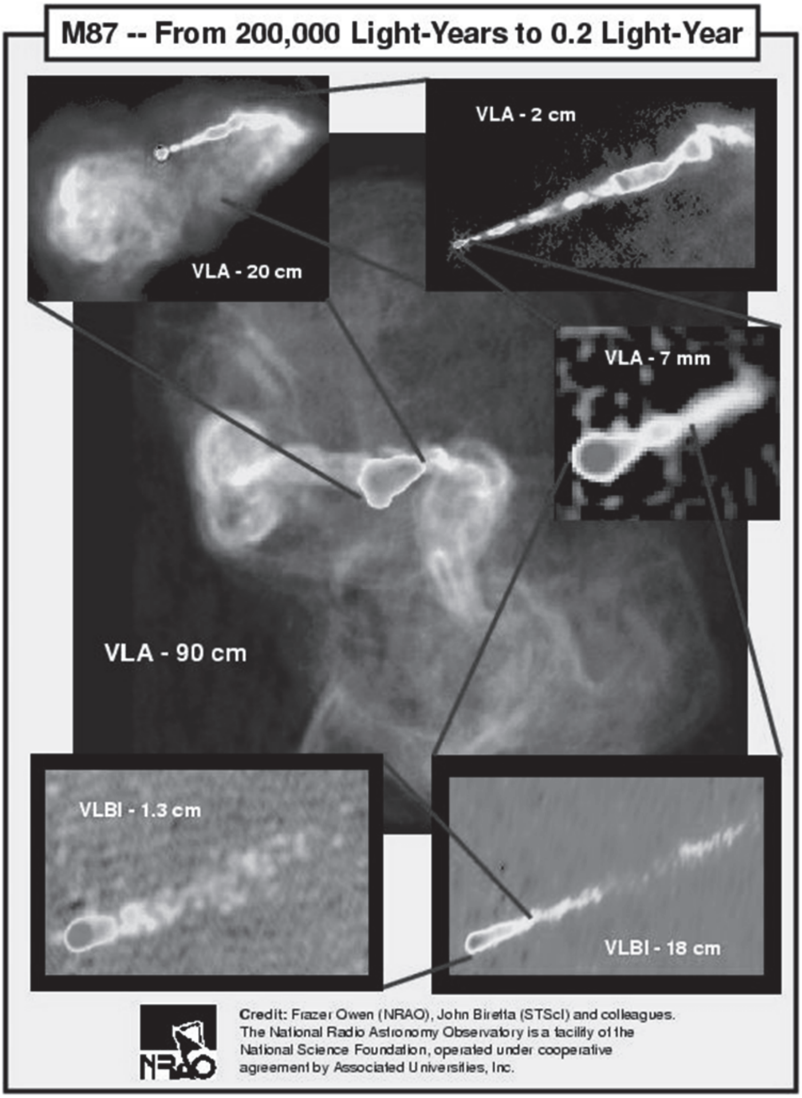


Figure 12. A series of multi-wavelength photos of M87 and its jets. Lobes of matter from the jet extend out to a distance of 250,000 light-years. Start in the center, then move to the upper left and follow clockwise the expansions of each image.

[i] The term 'black hole' was first publicly used in 1967 by physicist John Wheeler during a lecture. He always insisted that it was suggested to him by somebody else.

[ii] John Michell (1724 – 1793) was an English natural philosopher and geologist whose work spanned a wide range of subjects from astronomy to geology, optics, and gravitation.

[iii] Henry Cavendish FRS (1731 – 1810) was a British scientist noted for his discovery of hydrogen which he called inflammable air.

[iv] Michell, J. "On the Means of Discovering the Distance, Magnitude, &c. of the Fixed Stars, in Consequence of the Diminution of the Velocity of Their Light, in Case Such a Diminution Should be Found to Take Place in any of Them, and Such Other Data Should be Procured from Observations, as Would be Farther Necessary for That Purpose." *Phil. Trans. R. Soc. (London)* **74**: 35–57 (1784).

[v] Pierre-Simon, marquis de Laplace (23 March 1749 – 5 March 1827) was an astronomer/mathematician.

[vi] It represents the curvature in a Riemannian manifold. A tensor is a geometrical higher-order vector. Think of a matrix, although all matrices are not tensors.

[vii] Einstein called Λ his greatest blunder. Today scientists use it to explain 'dark energy'. It was originally introduced by Einstein to allow for a static universe (*i.e.*, one that is not expanding or contracting). This effort was unsuccessful for two reasons: the static universe described by this theory was unstable, and observations of distant galaxies by Hubble a decade later confirmed that our universe is, in fact, not static but expanding.

[viii] This allows one to measure intervals and to define distance in the curved space.

[ix] On the outbreak of war in August 1914 Schwarzschild volunteered for military service. While at the Russian front he wrote two papers on relativity theory providing the first exact solution to the field equations.

[x] A few months after Schwarzschild's work, mathematician Johannes Droste independently gave the same solution for the point mass.

[xi] Singularities are difficult to describe. They are absolute termination points – cessation of existence.

[xii] Actually Schwarzschild solved the equations with no mass and, then, in the weak field approximation, used the mass to bring it into coincidence with the Newtonian limit.

[xiii] Stationary means the black hole might rotate but not translate. A non-stationary black hole might be one that is orbiting another object.

[xiv] There are other metrics that are beyond the scope of this paper.

[xv] Bardeen J.M., Carter, B., Hawking, S., *Commun. Math. Phys*. **31**, 161-170 (1973)

[xvi] This means the infinity disappears in some coordinate systems.

[xvii] D. Finkelstein, Phys. Rev. **110**, 965–967 (1958).

[xviii] Which means we do not really know what happens.

[xix] It can orbit at this distance (and not fall in) if it moves quickly enough.

[xx] The $\sqrt{-1}$ is not allowed.

[xxi] *Science News*, **178**, p 28.

[xxii] See JWAS, Winter 2010 issue for a description of this experiment.

[xxiii] White holes cannot exist, since they violate the second law of thermodynamics.

[xxiv] Binary x-ray sources have a visible star and an invisible source of x-rays.

[xxv] Because angular momentum is conserved, observations of binary systems can give the total mass of the system.

[xxvi] 1 parsec is $3.08568025 \times 10^{13}$ km.