Black Holes Spin?

That's only one of several incredible new surprises about these whirlpools of darkness

By Robert Kunzig

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In the heart of MCG-6-30-15, a galaxy 130 million light-years away, there is a hole. It's as big around as the orbit of Mars. Into this hole stars and star-stuff are always falling—a lot of stuff, the equivalent of a hundred million suns so far. From this hole nothing escapes, not even light; it is perfectly black, like the mouth of a long tunnel. If you were to get into a spaceship and put it into orbit around this perfect blackness, you would find, once you got close enough, and even before you started your final descent into darkness, that you were no longer in control. You would be swept along by an irresistible current, not of swirling gas or stardust but of space-time itself.

That's because the black hole in MCG-6-30-15 is spinning. And as it spins, it drags space-time around with it.

No spaceship has been there to check it out, of course. And none of this is directly visible from Earth. From Earth, MCG-6-30-15 doesn't look like much: It's a lenticular galaxy, a lens-shaped blob of stars without the photogenic spiral arms that typify our Milky Way galaxy. "It's very undistinguished," says Cambridge University astronomer Andrew Fabian, who has been studying it for a decade. "If you were to use an optical telescope and just look at images, you wouldn't jump up and down." But if you look at the galaxy with a different kind of telescope, it comes alive. As gas falls toward the central black hole, before it disappears from the universe forever, it becomes so hot that it emits X rays, which astronomers can collect and plot on a spectrum.

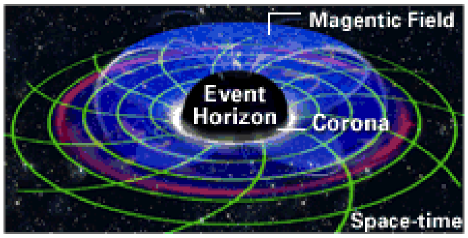
A team led by Jörn Wilms of the University of Tübingen in Germany has recently published the best spectrum yet for MCG-6-30-15. It doesn't look like much either, just a gently sloping line of data points, with a small spike at the top. But it was Figure 1 in the researchers' paper—there was no Figure 2—and although they did not actually jump up and down when they first saw it, they did get quite excited. "We just didn't believe what it was," says Wilms. That graph, he and his colleagues claim, says it all if you read it right: a giant black hole spinning at nearly the speed of light, the space-time around it twisted up like a whirlpool, and the fluorescent iron atoms that trace that fantastic motion cast like leaves on swirling water.

All that—and one more thing. The X-ray glow of those iron atoms is so intense that gravitational heating alone cannot explain it. What that unassuming little graph may represent is the detection of a new source of cosmic energy, one predicted a quarter century ago but never before observed. Some theorists believe a large fraction of all the light in the universe, including its most spectacular displays—jets of radiant gas that shoot out of certain galaxies at near light speed—may be generated this way. Its basic principle is familiar; Michael Faraday discovered it in 1831. But the setting is exotic, to say the least. If Wilms and his colleagues are right, there is not just a hole but also an electromagnetic generator at the heart of MCG-6-30-15, one that takes the rotational energy of swirling space-time and converts it into light, much as an alternator spinning atop an auto engine spits out electricity.

There was a time, before Faraday, when generators would have seemed more exotic than black holes; black holes were actually conceived first. The Reverend John Michell of Yorkshire, England, a geologist and astronomer as well as a clergyman, predicted their existence in 1784, using Newtonian physics. To Newton, light was made of particles with mass, and gravity was a force exerted by massive objects on one another. The more massive and compact an object, the greater the velocity required to escape its gravity. Michell calculated that a star 500 times as large as the sun and just as dense would have an escape velocity of the speed of light; light particles directed upward would fall back to the star's surface the way arrows or cannonballs do on Earth. Because light could never reach us from such a star, it would appear totally dark.

This is the misconception that most of us still harbor today, that a black hole is simply a star so massive that even light cannot escape it. The reality is more disturbing because a black hole obeys Einstein's rules and not Newton's. In a way, Einstein's rules, which were contained in the theory of general relativity he proposed in 1915, are more intuitive. Whereas Newtonian gravity was a mysterious force that somehow emanated from mass and acted instantaneously over long distances, in Einstein's view a massive object simply curves the space-time fabric around it. It thereby bends the path of anything traveling through space-time, including light. It does that despite the fact that light particles, or photons, have no mass, contrary to what Newton thought. In 1919, during a solar eclipse, the astrophysicist Arthur Eddington measured how the sun bent light from a star behind it. That shift, about one two-thousandth of a degree, agreed with Einstein's calculations and was verified in later tests to prove that Einstein, not Newton, had it right.

The gap between Einstein and Newton increases as gravity gets stronger and the curvature of space more extreme—black holes being the most extreme case of all. Einstein himself never believed they could exist. He was convinced that nature had a way, not yet discovered by physicists, to protect us from what he considered an absurd implication of his theory. Today, though, it would be hard to find a physicist or an astronomer who doesn't believe in black holes. One reason is that when enough mass is concentrated in a small enough space—as for instance in a large star that has exhausted its nuclear fuel—no force known can resist the implosive force of gravity.



Anatomy of a Black Hole

One of the weirdest implications of Einstein's general relativity theory is that as a black hole spins, it pulls space-time (represented below by green grid lines) along for the twisty ride. Recent observations of the galaxy MCG-6-30-15 suggest that the spinning of its central black hole inside a huge magnetic field produces power just like an electric generator. This energy contributes to the bright glow of iron atoms and other ultrahot matter swirling in a region called the corona.

Graphic by Matt Zang

That is what a black hole is, according to Einstein's theory of general relativity: a never-ending implosion. It is not just a star that is dark; it is an infinitely deep hole in the fabric of four-dimensional space-time. It forms when a massive object implodes and shrinks below a critical circumference, called the event horizon, and then keeps on imploding until all that mass is concentrated in a singularity—a point far, far smaller than a subatomic particle. At that point, space-time ends, and the pull of gravity becomes infinite.

"Think of a black hole not simply as a place where gravity is extremely strong but as a place where the fabric of space-time is being pulled continuously into the hole," says astrophysicist Mitchell Begelman of the University of Colorado, one of the authors of the Wilms paper. "Space isn't sitting there stationary outside the hole. It's always being stretched and pulled into the hole."

Time is being stretched, too. If you were to watch from a distant spaceship as a clock fell into a large black hole, you would see it ticking slower, and at the event horizon it would stop altogether. If your poor friend carrying the clock were to shine a light back toward you, you would see the light waves getting stretched out just like the ticks of the clock. This is called gravitational red shift. A light that started out blue would shift to red, then to infrared, then to radio wavelengths as it approached the event horizon. There the waves would become infinitely long, and the light would wink out.

Your doomed companion would be utterly unaware of this; in his frame of reference, his clock and his blue light would be behaving normally. (That's relativity.) He would not splatter off the event horizon, because it is not a material surface; he would fall through it without noticing a change. Your desperate signals to tell him to turn back would follow him into the hole, and he would receive them without difficulty. Perhaps he might respond with some poignant blue flashes of his own. But that last message would never reach you. Inside the event horizon, space is so curved that no paths out of the hole exist, even for light. Once your friend penetrated the horizon, the darkness would close over him. You would not see his fate—to be ripped into his constituent particles as he approached the singularity.

So that is a black hole: a place where the future leads only inward, with unpleasant results. Now imagine it spinning very rapidly.

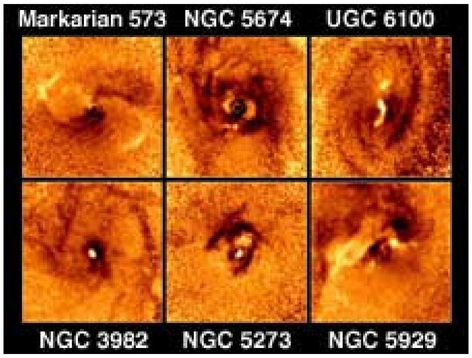
Most black holes must spin at least a little bit. Stars also spin, and when a large one collapses, the resulting black hole must spin even faster, for the same reason a spinning figure skater speeds up when she pulls in her arms. There may be millions of such black holes floating around our own galaxy, each five or 10 times as massive as our sun and roughly 50 miles around, each spinning more or less furiously—once a millisecond or so would be possible.

Black holes on an altogether different scale are believed to squat in the centers of most galaxies, including our own and MCG-6-30-15; the latest estimate has ours weighing in at a relatively puny 2.6 million suns. No one is quite sure how such monsters form. Perhaps it is through the spiraling collision of stars or star-size black holes in the overcrowded galactic core. In any case a giant black hole would be born spinning, and as more clouds of star-stuff spiraled into it, adding their angular momentum to its own, it would speed up. Ultimately, the theory goes, its event horizon should be moving at nearly light speed—the upper limit. A black hole with a mass 100 million times that of our sun, like the one in MCG-6-30-15, would have a circumference of more than 100 million miles, yet it could be rotating once every hour and three-quarters.

What happens to the space-time fabric that is being dragged into such a hole and is thus being spun around too? Does it get into such a fierce gnarly twist that it rips, spilling stars, planets, and general-relativity theorists out of the universe and into the cold nonexistence of hyperspace? Probably not. "I think you've reached the limits of the fabric analogy," says Begelman. Space-time is not really a fabric, he explains; it's a mathematical description of the possible motions of matter and energy. A black hole drags all the possibilities inward. A spinning black hole first drags them around with it for a while. Near the event horizon the drag is so strong that nothing can resist it. The only possible motion is to spin along with the black hole.

The mind reels, begs for a metaphor, a lifeline to a more familiar experience. "If you were to hover just outside the horizon but still under the influence of this twisting of space," says Begelman, "it would be as if you were riding on—let me think of another analogy—I would say it might be like a whirlpool."

Like a whirlpool but also like a flywheel, because the tremendous energy stored in that twirling patch of cosmos might actually be extractable.



Images of space-time whirlpools did not immediately pop up on Jörn Wilms's computer screen when he received his data from MCG-6-30-15. The data came from a satellite telescope called XMM-Newton, launched in 1999 and operated by the European Space Agency. (X rays from space don't penetrate Earth's atmosphere, so they must be collected in space.) XMM-Newton is on a distended orbit that takes it one-third of the way to the moon, which keeps it out of Earth's shadow long enough to stay pointed at—and collecting photons from—the same faint object for more than a day.

On June 11, 2000, X-ray photons that had left MCG-6-30-15 during the early Cretaceous Period 130 million years ago poured through the open hatch at one end of XMM-Newton. They glanced off gold mirrors, which focused the photons onto a silicon wafer at the other end, 25 feet away. This electronic detector recorded each photon individually. What Wilms received, back in his office in Tübingen, was a long list of several million individual photons posted on a Web site. It included the energy and arrival time of each one. Data do not get much rawer than that.

Cosmic Points of No Return

Black holes at the center of six active galaxies are caught in the act of reeling in huge swirls of interstellar dust and gas in combined visible and near-infrared images taken by the Hubble Space Telescope. This matter spirals inward, heating up violently and finally plunging into a black hole's event horizon. Because event horizons are tiny compared with the size of the galaxies they inhabit, no one has ever seen one; the smallest measured black hole presumably has an event horizon on the order of six miles across. For reference, the top left image is about 6,000 light-years across.

Photographs courtesy of Ohio State University/ Hubble Space Telescope

You don't see anything in such data without a theory of what you're looking at and looking for. MCG-6-30-15, the whole galaxy, is not much more than a point in the sky. Yet from previous observations of its spectrum, combined with lots of theoretical calculations, astronomers have sketched a picture of the intense activity in its nucleus. The central black hole, they believe, is girdled by a thin disk of gas that is spiraling inward toward doom. Most of this accretion disk is relatively cool, "which means its temperature is in the millions of degrees," says Wilms. At that temperature it glows mostly blue and ultraviolet.

The X rays must come from hotter stuff. The theory says they come from a tenuous, roiling foam of electrons and protons, called the corona, that splashes up from the disk near its center. As blue and UV photons stream through this billion-degree foam, they ricochet off its high-speed particles and are thereby boosted to X-ray energies—the whole band of X-ray energies, what astronomers call a continuum spectrum. To be at a billion degrees, the corona must be so close to the black hole that the in-falling gas has already converted most of its gravitational energy to heat. And because the corona is small, the X-ray emissions from MCG-6-30-15 can change fast. "We've seen its brightness double in a hundred seconds," says Andrew Fabian. "If you looked at it through an X-ray telescope, you would say, 'Wow!'"

More than a decade ago, Fabian and his colleagues discovered a way of seeing into this shimmering cloud, almost to the edge of its black heart; and it was this strange, subtle feature of the X-ray spectrum that the Wilms group went looking for. Some of the X rays from the corona, the Cambridge researchers realized, would shine back onto the accretion disk and excite iron atoms there. And some of those iron atoms would thereupon fluoresce, emitting X rays of their own—not over the whole band this time but at a single precise line in the energy spectrum: 6.4 kilo-electron volts, which is the energy an electron loses when it falls from one shell in an iron atom to a lower one.

An "emission line" like that in the hands of an astronomer is like a radar gun in the hands of a cop: It reveals how fast the X-ray-emitting iron atoms are traveling. Because the iron atoms in MCG-6-30-15 are moving, astronomers don't see the line right at 6.4 kilo-electron volts. Instead the X rays are Doppler-shifted, like a radar beam bouncing off a speeding car (the radar waves hit the gun more often if the car is moving toward the gun and less often if the car is moving away from the gun). The X rays are thus shifted toward the blue side of the spectrum, or "blue-shifted" to higher energies, and also intensified on the side of the accretion disk that is moving toward Earth; they are "red-shifted" to lower energies on the side that is moving away. When astronomers record a single spectrum for the whole galaxy, the iron line is smeared in both directions by this Doppler effect. At the same time it is also gravitationally red-shifted, because some of the iron atoms are very close to the black hole, where time itself and thus all light waves are stretched.

The net result is that the sharp emission line is smeared into a broad, asymmetrical hump—and the broader the hump, the faster the iron must be moving and the closer it must be to the black hole. Astronomer Andrew Fabian predicted all this in 1989. In

1994, working with Japanese researchers and the Japanese X-ray satellite ASCA, he found evidence for a broad iron line in MCG-6-30-15. Wilms and his colleagues hoped for more conclusive results with the more sensitive XMM-Newton.

"And what we saw right from the beginning was that the iron line was wrong," says Wilms. "It was much broader than what we thought it should be." The initial excitement was followed by fretting about whether they understood their own telescope. "Almost monthly, we'd have these panic attacks where someone would raise a calibration problem," recalls Chris Reynolds of the University of Maryland in College Park, who worked with Fabian on the earlier study and with Wilms on this one. "We'd have to do the whole analysis again."

The analysis consisted in building, brick by theoretical brick, a model of MCG-6-30-15 that would explain the data they got from the real galaxy. The researchers started with a model that included only continuum X rays from the corona; they found that it produced too many X rays at low energies and not enough at high ones. They added a cloud of warm haze a few light-years from the black hole to absorb some of those low-energy X rays. (That haze really seems to exist; it's what makes MCG-6-30-15 look dull in visible light.) They supplemented the X rays coming directly from the corona with ones that had reflected first off the disk—and found they were still coming up short. Finally, they added a fluorescent iron line, amazingly bright and red-shifted so strongly that it had to be coming from iron atoms streaking just over the event horizon at near light speed. Bingo.

"It was almost like a blazing ring right around the black hole," says Reynolds.

For the iron atoms to get that bright so close to the black hole in MCG-6-30-15, the hole has to be rotating rapidly. By dragging space-time around with it, a rotating hole allows gas to orbit closer to the event horizon without falling in. And if the iron atoms are fluorescing that brightly, it means something is wrong with the standard model of black-hole accretion disks. In that view the disk is lit up by only gravitational energy, which is converted into heat and light by means of friction. But it's hard to generate blazing rings that way. "The gravitational energy is released gradually, so the glowing region of the accretion disk is fairly extended," says Reynolds.

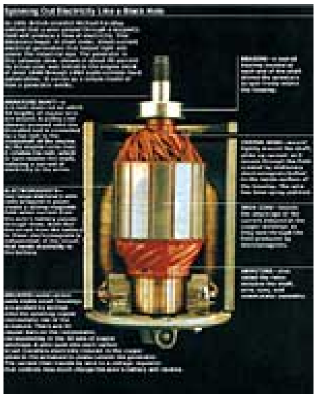
"There's no way you can produce more energy, say, by throwing the stuff down the black hole faster," says Wilms. "You really need some other mechanism."

"If what we're seeing is what we think we're seeing," says Mitch Begelman, "then it's very significant."

The new mechanism for getting energy out of a black hole is not really new. Roger Blandford and Roman Znajek of Cambridge University proposed it in 1977. And the reason you can get energy out of a black hole, that swallower of all things, is that the energy you detect never really got into the black hole to begin with—it's associated with the space-time whirlpool created outside the event horizon by the black hole's rotation.

Magnetic fields, Blandford and Znajek realized, could convert that rotational energy to electricity. The accretion disk is made of charged particles, and when the particles move, they generate a magnetic field. From then on, the field lines and the gas tend to stick together and move together. When the gas plunges into the black hole, it follows the magnetic field lines. In Blandford and Znajek's theory, these lines protrude from the event horizon like quills from a porcupine. Passing first through the space-time whirlpool, they continue far beyond it into quieter realms. The whirlpool whips these magnetic field lines around.

Spinning Out Electricity Like a Black Hole



Click on image to enlarge (76K)

It was Michael Faraday who discovered what happens when a magnetic field moves through an electrical conductor, or vice versa—though he certainly didn't have the ionized gas of an accretion disk in mind. "Faraday said changing magnetic flux generates an electromotive force—a voltage, if you like," says Blandford, who is now at Caltech. "That's the basis of simple generators. It's the same thing here. We've got a black hole that's spinning, so it's moving magnetic fields around it, and that creates voltages. This time, though, the voltages can be prodigiously large." In theory the voltage difference between the black hole's poles and its equator can be billions of trillions of volts.

You can think of the magnetic field lines as wires in a titanic electric circuit, with the black hole as the generator; or you can think of them as elastic bands that literally fling electrically charged particles into distant space as they themselves are whipped around by the rotating black hole. The black hole acts like a flywheel: As matter falls into it and increases its spin, it stores energy; it releases energy again and slows down a bit as the magnetic field lines accelerate charged particles. "Probably what may happen is that you twist up the field lines by a certain amount, and then they snap back," Begelman speculates. "Then you twist them up again, and they snap back. This would happen in an unsteady and somewhat unpredictable way, and as a result you would extract the energy in fits and starts."

That sort of pulsing certainly goes on in cosmic jets, which are what Blandford and Znajek invented their theory to explain. Jets are narrow streams of gas that emerge from the cores of some galaxies, travel at more than 99 percent the speed of light, and penetrate as much as several million light-years into intergalactic space before fanning out into broad, luminous lobes. How might a black-hole whirlpool generate such a pair of waterspouts? Swirling bundles of magnetic field lines, flinging particles outward from the poles of the hole, provide a natural explanation. It would be nice, though, to have some direct observational evidence for the theory; Blandford has been waiting a quarter-century for that.

MCG-6-30-15, unfortunately, has no jets. For an active galaxy it is relatively quiet. But it does seem to have that blazing ring right around the black hole—and at the moment, say Wilms and his colleagues, the most plausible source of that light is some type of electromagnetic generator powered by the rotation of the black hole. The details of the mechanism have yet to be hashed out—and a lot of people are now motivated to work on it. "The theorists have been talking about this kind of process for years," says Reynolds. "But until now there's never really been an observation you can point to and say, 'We think we have hard facts.'"

How hard are those facts? There is no doubt that the observation Wilms and his colleagues made was hard in another sense—"at the limits of our current technology," as Begelman puts it. The only easily recognizable thing on their Figure 1 is the little spike at the summit of the spectrum: That's the iron line, right where it should be, at around 6.4 kilo-electron volts. But it's the *unshifted* iron line, made by slow-moving iron atoms far from the black hole. The broad iron line, the feature they were looking for, is so broadened that it is almost horizontal, an extra stratum laid over the continuum X rays from the corona. So it is hardly rude to be skeptical. "It's very tricky telling what's the feature and what's the continuum," says Julian Krolik of Johns Hopkins University, one of the theorists now trying to figure out how magnetic fields could convert a black hole's spin energy into light. "We're all a little anxious about this."

More data may soon dispel the anxiety. Fabian's team has recently observed MCG-6-30-15 again with XMM-Newton—watching it for three times as long as the Wilms team did—during which time it got twice as bright; they too found a broad iron line. And last fall Fabian and fellow astrophysicist Jon Miller of the Massachusetts Institute of Technology recorded an uncannily similar spectrum from a stellar-mass black hole in our galaxy. "It looks just the same as MCG-6-30-5," says Fabian.

Perhaps the remarkable thing is that there should be any observational evidence at all for so outlandish a phenomenon. "We're testing some of the most exotic predictions of the theory of black holes," says Begelman. "Even beyond the idea that they themselves can exist—the idea that a black hole can actually grab on to space and twist it around, forcing everything in the vicinity to spin." Einstein himself couldn't accept the first idea, even as a matter of theoretical principle; now scientists are on the verge of actually measuring the second one. Which doesn't mean they find it any easier than the rest of us to imagine a space-time whirlpool.

"I can do the math, and it pops out," says Wilms. "But I always have big problems imagining it."

Two X-ray Telescopes Are Better Than One

Photographs: top to bottom, courtesy of STSCI/NASA; courtesy of European Space Agency.

XMM-Newton (right, bottom) is not the only telescope casting a prying eye on the violent X-ray universe. NASA's own five-ton workhorse is the orbiting Chandra X-ray Observatory (right, top), launched in July 1999. Like its European counterpart, Chandra has an elongated orbit swinging it from about 6,000 miles above Earth's surface to nearly 87,000 miles away. Chandra and XMM-Newton both detect a wide range of X-ray sources, from the "soft," lower-energy emissions of supernova remnants up to the energetic beams from black holes and neutron stars. (Another satellite, NASA's Rossi X-ray Timing Explorer, monitors ultrahigh energy signals from those objects.)

So why have two big observatories? "They are actually quite complementary," says Steve Snowden, an astronomer with the XMM-Newton Guest Observer Facility at NASA's Goddard Space Flight Center in Greenbelt, Maryland. Chandra's four sets of X-ray-reflecting mirrors are smoother and more accurately shaped and aligned than are XMM-Newton's 174 nested mirrors. "It has much clearer vision. It is able to resolve finer objects in the sky," Snowden says, and pick out details in complex structures like supernova remnants and star clusters. But the large surface area of XMM-Newton's mirrors takes in five times the number of X rays and views a larger patch of the sky, "so it is very useful for looking at large structures," adds Snowden.

— *Kathy A. Svitil*

Web Resources:

Check out a tutorial on black holes: www.howstuffworks.com/black-hole.htm.