Microquasars Raise Megaquestions

To uncover the machinery behind galaxy-spanning quasars, astrophysicists are scrutinizing their miniature counterparts—only to find that they pose puzzles of their own

Contrary to popular belief, black holes are finicky eaters. Although the voracious billion-solar-mass monsters that power distant quasars can devour the equivalent of one sun per year, they may spit out as much as they swallow.

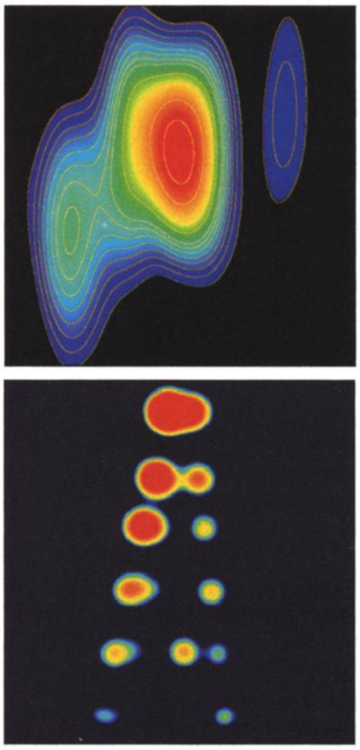
For decades, radio astronomers have seen narrow jets streaming out of the centers of quasars and pooling up in vast "lobes" that resemble the outstretched ears of an elephant. Despite intense study, however, "jets have resisted understanding," says astrophysicist Jean Swank of the Goddard Space Flight Center in Greenbelt, Maryland. What they are made of, why they form, what keeps them going—all are unsettled questions.

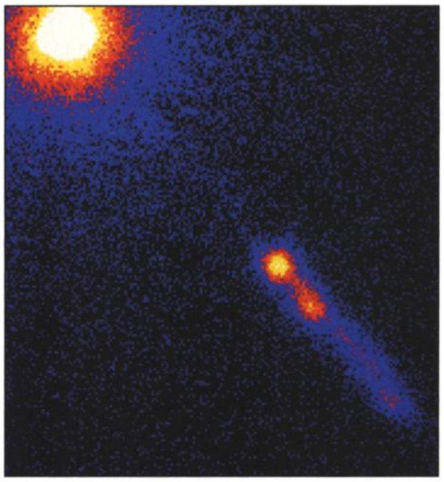
The problem is that quasar jets change very slowly. Although individual blobs in the otherwise smooth jet sometimes appear to travel faster than the speed of light—an optical illusion called superluminal motion, produced when an object travels toward Earth at nearly the speed of light—the jets are very long. A single lobe can be as long as the spiral arm of a galaxy. As a result, it can take decades for astronomers to notice any movement or change in the shape of a quasar jet.

So Felix Mirabel of France's Atomic Energy Commission (CEA) in Saclay and Luis Rodriguez of the Institute of Astronomy in Morelia, Michoacán, Mexico, were thrilled when, in 1994, they spotted a pair of miniature radio jets erupting from a nearby galactic black hole candidate named GRS 1915+105. Like the jets from its grandiose relatives, the newly christened microquasar emitted an occasional blob that raced down the length of the jet at superluminal speeds. In fact, the tightly focused jets were almost exact small-scale replicas of parsec-sized quasar jets, with one crucial difference: They evolved in minutes, not years.

"Microquasars are an ideal test laboratory for jet formation," says Cornell University astrophysicist Stephen Eikenberry. Their appetites whetted, astronomers started avidly hunting for more. Since Mirabel and Rodriguez's discovery, concerted observations from the ground and from space with radio, infrared, optical, x-ray, and gamma ray telescopes have turned up about a dozen objects with the telltale microquasar radio jets.

Just how much microquasars have to say about normal-sized quasars, however, is hotly debated. Do they really hold the key that will unlock the mysteries of jet formation in quasars? Or are the apparent similarities just a coincidence? Answering these questions is one of the primary goals of a new generation of orbiting x-ray telescopes, including the Chandra X-ray Observatory, the Rossi X-ray Timing Explorer, and the European Space Agency's XMM-Newton and Integral satellites.





Jet set. Oblong blobs of light mark where microquasars (*above*) and quasars (*right*) shoot geysers of gas into space.

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Some astronomers think the family resemblance will turn out to be spurious. "So far, nothing we know about quasars has been changed by observing microquasars," says Bruce Margon, an astronomer at the University of Washington, Seattle. The black hole that powers a microquasar, Margon notes, is about as massive as a star; the hole in a "real" quasar is a billion times larger. "Very few physical processes scale linearly over nine orders of magnitude," he says. The dining habits of the two types of objects also seem to set them apart. Quasar black holes are isolated beasts that feed on hot gas dribbling in from a surrounding cloud. Microquasar black holes are more social: Every known microquasar orbits a windy gas-giant companion star that dumps material into the black hole.

Whatever its source, scientists believe that as gas approaches the central black hole of either a quasar or a microquasar, it collapses into a disk that whirls around the hole in much the same way as the planets orbit the sun. Unlike the planets, however, the viscous gas in a so-called accretion disk gradually loses energy and spirals toward the hole. The lost orbital energy heats the disk, so the temperature of the gas increases the closer it gets to the black hole. As the gas prepares to drop into the black hole, its temperature skyrockets toward almost 1 billion degrees and radiates copious x-rays.

The jets of a quasar, many theorists suspect, result from the way the gas interacts with the loops of its own magnetic field. The rotating disk winds the field loops like the rubber band in a toy airplane. The magnetic tension increases as the field loops approach the black hole, weaving the loops into magnetic braids that pop out perpendicular to the disk. Hot, radiating gas flows up from the disk and through the braided field lines like water through a pipe, forming the illuminated, magnetized fountains that astronomers call jets.

Theorists think similar scenarios can explain microquasars, with one key difference: Quasar jets appear to be steady and unchanging, whereas microquasar jets are anything but. In GRS 1915+105, for example, approximately every 30 minutes a new blob of radio emission materializes at the base of the jet, accelerates to superluminal speeds, and rockets outward along the jet, fading as it goes. In other microquasars, the light from the jets fluctuates wildly. By comparing radio and x-ray observations of microquasars, astronomers have found evidence that the superluminal blobs and variations in x-ray brightness both result from processes that take place when a microquasar flip-flops between two very different states.

"The x-rays from accreting black holes in our galaxy come in two distinct forms," explains Rob Fender, an astrophysicist at the Astronomical Institute–Anton Pannekoek (AIAP) in Amsterdam. In the so-called high/soft state, the disk shines brightly in low-energy "soft" x-rays. As the microquasar enters the low/hard state, on the other hand, the x-rays dim but their spectrum shifts to higher energy "hard" x-rays. Now, independent observations by Fender, Eikenberry, Mirabel, and their collaborators indicate that the superluminal radio blobs from GRS 1915+105 form as the microquasar makes that transition. And Michel Tagger, an astrophysicist at the CEA, thinks he can explain why.

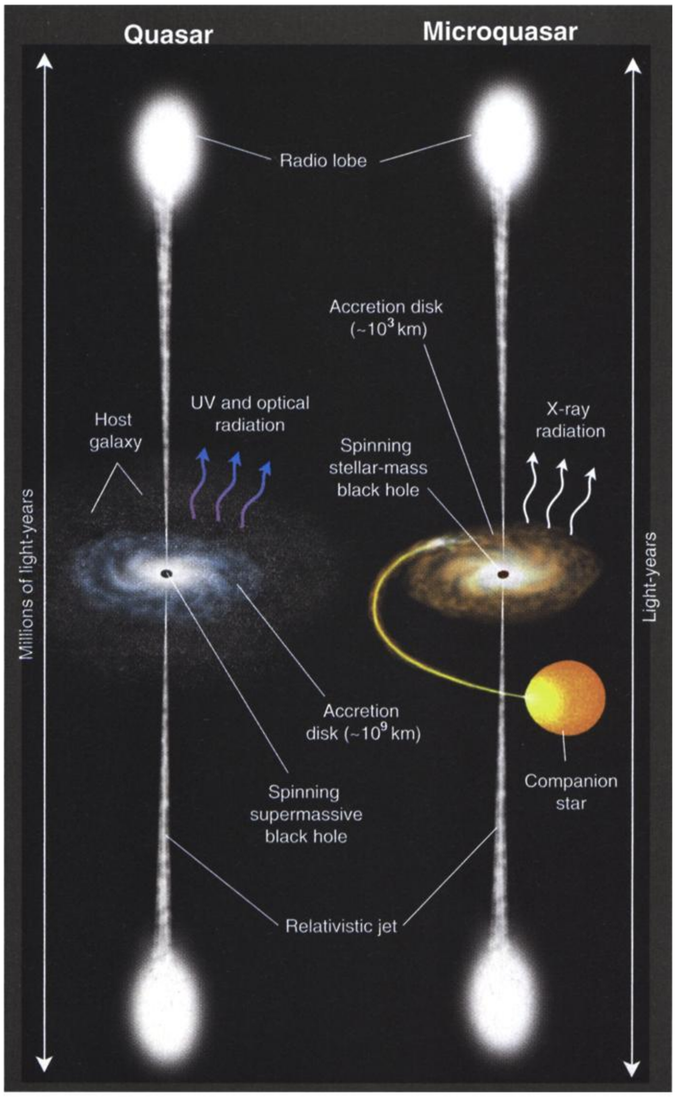
A theory developed by Tagger's team and confirmed by computer simulations shows that magnetized accretion disks naturally spawn spiral waves, in much the same way as the Milky Way disk generates spiral arms. In Tagger's model, a microquasar spends part of its time in the high/soft state, during which the waves sweep the magnetic field inward toward the brink of the black hole—the so-called "innermost stable orbit," a mere 100 kilometers from the hole. Closer in, the black hole's gravity grows so strong that nothing can remain in a circular orbit; the accreting gas plunges straight into the hole.

The magnetic field, however, doesn't follow the doomed matter. Instead, it piles up at the edge of the hole until the increasing tension in the twisted field suddenly snaps it like a rubber band that has been stretched too far. The explosion destroys the soft-x-ray–emitting inner part of the disk, allowing the hard x-rays to shine through and returning the microquasar to the low/hard state. At the same time, the energy of the broken field launches a blob into the jet, as observed in some microquasars. Astrophysicists say that if the theory can be extended to quasars, it might explain the mysterious dichotomy between radio-loud quasars, which emit jets, and the more numerous radio-quiet ones, which have no jets at all. Radio-quiet quasars could simply be in the supermassive equivalent of the high/soft state.

Tagger's theory rests on one big assumption. For it to work, the accretion disk must extend all the way down to the innermost stable orbit of the black hole. In the gravitational hurly-burly near a black hole, however, any number of forces could destroy or scatter the gas en route. Does it really reach the crucial 100-kilometer point? Tiny variations in the x-ray flux from the microquasars are whispering that the answer might be yes—at least some of the time.

The gravitational pull of a microquasar black hole forces disk material to orbit the hole approximately 1000 times per second, just as the sun's gravity pulls Earth through one complete revolution every year and makes the planets in tighter orbits speed around much more quickly. A tiny clump of gas in the innermost orbit would hurtle along at nearly the speed of light, and on each pass it would shine a beam of x-rays at Earth like the headlights of a car on a circular track.

In fact, signals resembling such x-ray "headlights" have been detected. Astronomers studying microquasars have measured x-rays that rise and fall at a rate that wanders around a fixed central frequency—sometimes slightly higher, sometimes slightly lower. First discovered in 1985, these quasi-periodic oscillations (QPOs) have now been found in most known microquasars. The typical QPO frequencies are suggestively close to the period expected for a lump of gas in the innermost stable orbit of a black hole. The hitch, so far, is that the orbiting-gas model is only one of many possible explanations of the variations in frequency. Those variations—the "quasi" in quasi-periodic—make scientists wary of overinterpreting the results. "The frequencies of these QPOs are definitely in the right ballpark, but other processes could mimic the effect," says AIAP astrophysicist Michiel van der Klis.



Mini-Me. Similarities between quasars and their micro counterparts belie the billionfold difference in their black holes' mass.

Another test of the magnetic-jet theory is to measure the speed of microquasar jets. Tagger's model predicts that the disk-hole system should spew out material at nearly the speed of light. The superluminal blobs detected in three microquasars fit that picture very well. Calculations show that to create the illusion of faster-than-light travel, those jets must be coursing along at 80% to 90% of light speed, at minimum. The velocity has been measured for only one microquasar, however. "If we had even one more velocity, we could at least ask the fundamental question: Are all the velocities the same?" says Margon. "Right now, we can't even do that."

Clocking a jet's speed directly is difficult, because microquasars' distances are poorly known. In principle, exact measurements could come from the jets' light. A stationary hot gas of atoms radiates light at specific frequencies that form bright "emission lines" in the spectrum of light from the gas. The emission lines of two oppositely directed high-speed jets of hot gas, however, split into pairs. The same Doppler shift that raises the pitch of an approaching train whistle also increases the frequency of the emission lines from a jet pointed in our direction. The emission lines from the receding jet drop to lower frequencies. The difference in the two Doppler-shifted line frequencies is directly proportional to the jet velocity.

So far, astronomers have found the revealing line pairs in only one object: SS433. Unfortunately, that reading has just sown

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more confusion. SS433's emission lines show that the jet streams outward at one-quarter of the speed of light—fast, but not as fast as theory predicts. And there is another problem: Some astronomers suspect that SS433 is an anomalous object that contains not a black hole but a neutron star—"the worst example" of a microquasar, Margon says.

Help may come from Chandra, which has recently turned up encouraging hints of line pairs in several other microquasars. "We found suggestive evidence for the lines in the microquasar 1E1740.7-2942," says astrophysicist Wei Cui of Purdue University in West Lafayette, Indiana. "We now have 10 times more telescope time, so we should have a definitive answer next year."

Until that answer comes, researchers can only speculate as to whether microquasars truly are miniature quasars. Dimitrios Psaltis, for one, is beginning to suspect that the answer isn't a simple yes or no. Psaltis, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, in collaboration with van der Klis and Tomaso Belloni of the AIAP, has found evidence that the pattern of QPOs varies smoothly from neutron stars to black holes. The result suggests that microquasars are not exactly the same as either neutron stars or quasars, but instead form a link in a chain of jet-producing compact objects that extends from stellar-mass neutron stars all the way to the supermassive quasars.

Van der Klis acknowledges that the proposal is tentative and needs further investigation. "Some say this is just a coincidence, and others build entire theories out of it," he says. "That is just the way it is in this field right now." —MARK SINCELL

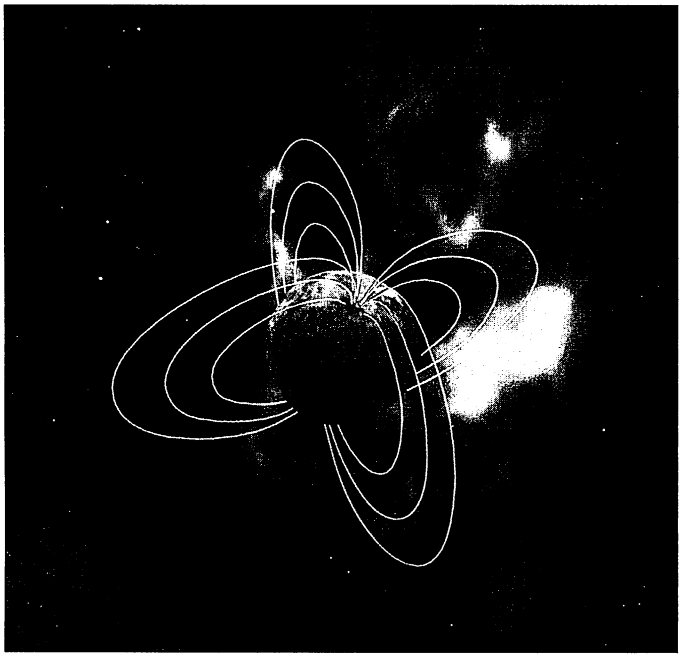
Mark Sincell is a science writer in Houston.

NEWS

Astronomical Odd Couple? Or Alter Egos?

While theorists try to bring them under one explanatory umbrella, the cosmic rarities known as SGRs and AXPs seem to insist on their differences

To high-energy astrophysicists, the calm beauty of the night sky is the world's grandest illusion. "It's a wild animal park out there," says Chryssa Kouveliotou of NASA's Marshall Space Flight Center in Huntsville, Alabama. Kouveliotou should know. She and a handful of colleagues worldwide study two of the wildest, most elusive creatures in the universe. Known as soft gamma repeaters and anomalous x-ray pulsars—SGRs and AXPs for short—the two classes of objects have teased astronomers for years with tantalizing similarities that may, or may not, be family resemblances. For the sake of simplicity, astrophysicists would love to show that SGRs or AXPs are special cases of the same theory, or different stages in each other's life cycle. So far, though, attempts to establish such an evolutionary link have run up against equally frustrating differences between the two enigmatic objects. And some recent evidence indicates that they may not be related at all.



Dynamic. Whirling fluid inside a young neutron star generates a magnetar's intense enormous field—the probable powerhouse behind soft gamma repeaters.

The likenesses are clear: Both types of objects are rare; astronomers know of only four SGRs and six AXPs. Both are found alone, apparently in association with young supernova remnants. From variations in their x-ray output, astronomers know that both spin with periods of between 5 seconds and 12 seconds, and both are slowing down considerably.

The main differences between them are that SGRs have a "harder" spectrum (one containing more high-energy radiation), and, unlike AXPs, they erupt into bursts of explosive activity. But those distinctions may not be hard and fast. The first identified SGR—an object known as SGR 0526-66 in the Large Magellanic Cloud—would be classified as an AXP if it were discovered today, Kouveliotou says. No one has detected a burst from 0526-66 since 1983, and a team led by Shrinivas Kulkarni of the California Institute of Technology in Pasadena, which recently observed the object using NASA's Chandra X-ray Observatory, reports that its spectrum turns out to be very soft.

"The similarities of SGRs and AXPs argue that they are one kind of beast," says Robert Duncan, a theoretical astrophysicist at the University of Texas (UT), Austin. And the heart of the beast, everyone agrees, is a neutron star—the whirling, superdense corpse of a massive star that exploded as a supernova at the end of its short life. Beyond that, though, confusion begins. At issue is how the two objects generate the powerful radiation in their spectra. The reigning model of SGRs says that it comes from starquakes on the star's intensely magnetic surface. A popular model for AXPs holds that the radiation emanates from gas sucked in by the star's enormously powerful gravity. If the beasts are indeed related, at least one of the models must be wrong. Which one? The experts disagree, often sharply.

Surging starquakes

The SGR saga began in 1979, when orbiting satellites and interplanetary space probes registered a couple of powerful bursts of energetic x-rays and gamma rays. No one knew what they were. Most astronomers classified them as gamma ray bursts. (See the Review by Peter Mészáros on p. 79.) One of those explosions, however, was special. Observed on 5 March 1979, it appeared much brighter than any other gamma ray burst detected so far, it contained more low-energy radiation, and it went off again and again, producing 16 bursts over a 4-year period. What's more, whereas "normal" gamma ray bursts occur in "empty" spots on the sky, this one—called SGR 0526-66, after its position in the sky—resided in a young supernova remnant in the

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