Black Holes on the Swing

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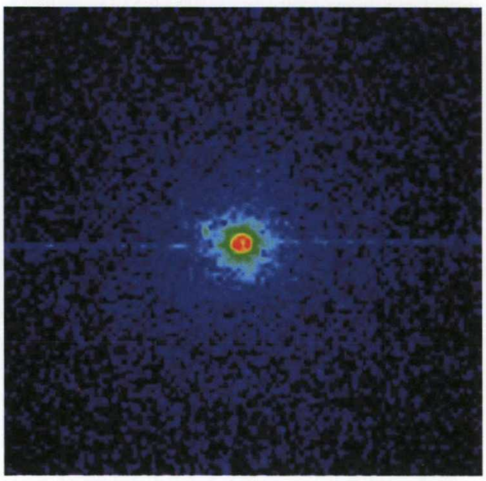
Just as Isaac Newton weighed the Earth by thinking of the Moon as a falling apple (or so the story goes), so we can weigh certain unseen monsters that are devouring their companion stars. What are these objects that have masses several times larger than that of our Sun, and yet are only a few miles across? In fact, everyone knows their name: black holes

Astronomers now think that the core of every galaxy harbors a black hole of gigantic proportions. Some, such as the one at the center of our own Galaxy - named Sagittarius A* for the constellation (one of the twelve signs of the Zodiac) where it resides - are hiding from scrutiny. Others are as easy to detect as a noisy neighbor's household appliance. Like a giant vacuum cleaner they suck in nearby matter, thus forming a shrieking tornado that can easily be "heard" by astronomers. The swirling maelstrom heats the infalling gases till they are white hot, X-ray hot to be precise, up to temperatures of hundreds of millions of degrees. So much gas is being heated, and to temperatures so high, that this matter about to be swallowed by a supermassive galactic black hole easily outshines billions of stars. Think of a beacon that can be seen a hundred million light years away, or more. Just as a waterfall is accompanied by a rising mist of fine spray, so do these black holes eject some of the matter that initially falls in. This "spray" often takes the form of two narrow streams of gas escaping the vicinity of the black hole at nearly the speed of light.



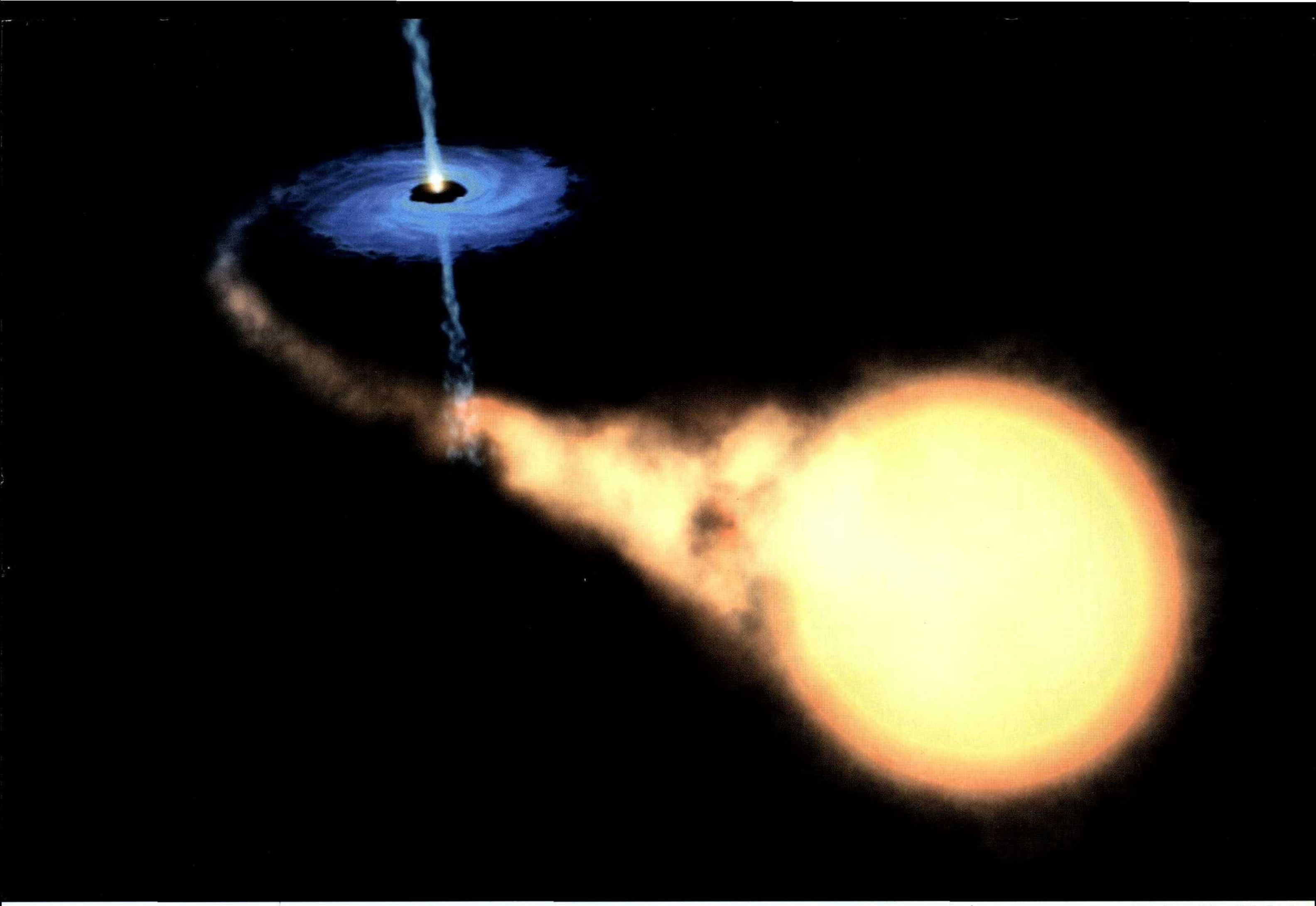
NASA/SRON/MPE

Cygnus X-3, a microquasar at a distance of about 30,000 light years, hides one of the most famous stellar black holes in the Milky Way

Monsters in miniature

In a surprising discovery, a few years ago X-ray and radio astronomers discovered small scale models of the supermassive black holes that are known from studies of distant galaxies.

In the world of black holes, the all-important measure is mass. Everything that happens in a black hole weighing as much as a billion suns also happens in a black hole weighing "only" ten times as much as the Sun, except that it happens much more quickly because the sizes involved are much smaller. Close to a black hole everything moves at the speed of light, and as the time needed to travel somewhere at a fixed speed is proportional to the distance covered, so the time for anything to happen close to a black hole is simply proportional to the linear size of the black hole. And the linear size is proportional to the mass - a black hole weighing ten times as much as the Sun is about thirty kilometers across, while a black hole weighing ten million times as much as the Sun is about thirty million kilometers across. Thus, something that may take years to happen in a supermassive black hole (say a billion Suns) in a distant galaxy, will take only a fraction of a second in any of the several black holes now known in our Galaxy, each of which weighs as much as ten Suns. Since the active black hole beacons millions of light years away are called quasars, their small-scale models in



European Space Agency, NASA and Felix Mirabel

Microquasars are black holes of about the same mass as a star, pulling material from their ordinary stellar companions

our Galaxy have been dubbed microquasars by their discoverer Felix Mirabel. They are thought to be systems in which a black hole pulls matter off a star that orbits around it.

Astronomers have historically been known for their patience - our understanding of celestial motions emerging only after centuries, if not millennia, of painstaking observations. Yet in today's fast paced world it seems much easier to closely monitor a microquasar for a few hours, and then to analyze each fraction of a second's worth of data, than to observe a distant quasar day after day for several decades. One reason for this is that much of what there is to observe needs to be recorded by satellite instruments (X-rays do not penetrate the Earth's atmosphere and do not make it to ground-based instruments) and these simply do not last in good working condition for more than a few years. In fact, most instruments ever launched into orbit have long since burnt up in the atmosphere, as the satellite orbits have decayed. This makes microquasars ideal objects for studying what may happen next to a black hole.

As it turns out, most of the time microquasars do not do very much, with their black hole hardly detectable at all. What is detected in those prolonged periods of inactivity (technically called quiescence) is the light from an ordinary star, which can be observed through ordinary telescopes. Studying stars through a telescope is something astronomers know very well how to do, and each of these ordinary stars was found to orbit an unseen companion, whose mass was found to be six solar masses in one system, ten in another, and so on.

Every now and then, the microquasars become very active, suffering what is known as an outburst. Suddenly, they become very bright, much brighter than ordinary stars, and they emit radiation of different wavelengths, in various radio bands as well as optical light, i.e., light of ordinary colors, but also light bluer than any we can see with our own eyes ("ultraviolet"), and even X-rays. This means that the emitting region becomes very hot. If we were to heat a fire poker in a really hot fire, it would first glow red, then yellow, then blue, then ultraviolet, and eventually emit X-rays (of course it would have melted down first). By measuring the amount of radiation emitted by the "poker" and observing its color, scientists can determine its size. The color of the glow (in this case X-rays) determines the temperature, and once the temperature is known the intensity of radiation is simply proportional to the surface area of the "poker." Actually, we do not need a poker at all, as we can do the same directly for the fire. When this method of investigation was applied to the fiery outbursts of microquasars, an extraordinary result was obtained.

The fire, here really a mass of heated gases, envelops the previously unseen companion whose mass is six or ten times the mass of the Sun, and yet the total surface area of this extremely hot gas is no bigger that of a large lake, perhaps one of the Great Lakes in North America. How can you fit something as heavy as several stars beneath a surface area so small? You can do so, provided that something is a black hole.

Flickering flames of a microquasar

A microquasar in outburst is not a steady beacon; its erratic light is more reminiscent of the flame of a torch in strong wind. When these variations in brightness were carefully analyzed by US X-ray astronomers Ron Remillard, Jeff McClintock and Ted Strohmayer, and by others, the result came as a big surprise. The X-rays varied very quickly, and some of the variations were almost regular. The X-ray torch became brighter and dimmer several hundred times a second. If these were sound waves rather than X-rays, we would be able to hear these variations as a tone, fixed for each of the black hole sources. Think of a foghorn.

The higher the mass of the black hole, the lower the tone. For instance, for one source weighing as much as six Suns, the variation occurred nearly regularly at a rate of 300 times per second! This number is less surprising if we recall that a black hole weighing this much is only about 20 kilometers across, and that close to the black hole things move nearly at the speed of light. Thus, a clump of

Preparations for launch of NASA's Chandra X-ray Observatory in 1999

NASA


NGST

hot gas orbiting such a black hole would revolve around it some 300 times a second in a circular orbit only 80 kilometers in radius. Clearly, Formula 1 races are not half as exciting as this.

An even bigger surprise was that each black hole gives out not one, but two regular tones. As Marek Abramowicz of the University of Göteborg and the present author pored over the data, we realized that these two tones were in consonance, known in music as a quint - the two tones were in a 3:2 ratio (e.g., 450 vibrations a second and 300 vibrations a second). What could be the source of this music? According to historians of science, a similar discovery actually gave birth to physics. Pythagoreans discovered that the tones of a lute depend on the length of the strings that are plucked - the longer the string, the lower the tone. To get a quint, one simply needs to pluck two strings whose lengths are in a 2:3 ratio. What are the strings around the black holes, and why are those particular strings plucked? No one is sure, but we do have an idea.

Einstein's swing

It is known that the hot gas enveloping a black hole forms a flat disk, much like the rings of Saturn. The gas, initially cascading down from the ordinary companion star that is slowly being cannibalized by the black hole, swirls around and around the black hole until it is spread out in a thin disk. In this disk fluid slowly spirals down towards the center, but in so doing it snakes around, much like a meandering river. The sinuousity of the river brings the fluid sometimes closer to the black hole, sometimes farther out. In our view, the roar of the meandering river is the first foghorn. This is the lower tone (e.g., 300 times a second). At the same time the flow can also be deflected out of the plane of the disk. It is as though one of the rings of Saturn were lifted above the others and let go - it would then oscillate up and down for a while. This up and down oscillation is the second tone. And the reason behind the quint is then not a mystery at all.

Imagine a lute with many strings of lengths similar to the length of the string you happen to be plucking. If one of those strings is exactly 2/3 the length of the string being plucked, it will also vibrate on its own in the lute. This phenomenon, which is known as a resonance, is familiar to every child who has been on a swing. To make the swing move pendulum-style up and down (which is the fun part) we must move our legs forward and backwards in tune with the swing. We can move just as often as the swing, or twice as often, and the swing will respond. Or, on a very hot day when we feel lazy, we can move more slowly than the swing, moving our legs only two times for every three movements of the swing. This is how it works in black holes. In contrast, gas moving around an ordinary star, or the rings of Saturn, would never be so lazy - for each forward and backward movement there would be only one up and down movement, and there and then only a single foghorn would sound.

Violin aficionados can tell a Stradivarius from an Amati by its sound. X-ray astronomers can tell a black hole from an ordinary star by the sound of the X-rays. Two foghorns in a quint a black hole betray. ■

X-rays do not penetrate the Earth's atmosphere and have to be observed by space telescopes, like NASA's Chandra X-ray Observatory, shown here in an artist's illustration

Further reading:

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