All in the Timing

Taking a tape measure to neutron stars

By RON COWEN

They are the most outrageous of stars. Neutron stars squeeze more matter than the sun into a sphere only 20 kilometers wide, wield the strongest gravity outside of a black hole, and spin at a dizzying rate, up to several hundred times a second.

The very oddness of these bodies, the shrunken remains of dead stars, enables scientists to test fundamental theories about gravity and the density of matter. Where else could astronomers hope to study the behavior of elementary particles at densities five times greater than densities inside an atomic nucleus? The immense gravity of neutron stars strongly curves space-time, putting general relativity—Einstein's theory of gravitation—through its paces in a way that other objects simply cannot.

"If you want to test physical theory, you want to push it to its extreme," says Michiel van der Klis of the University of Amsterdam. "Only then can you start to see if it really works."

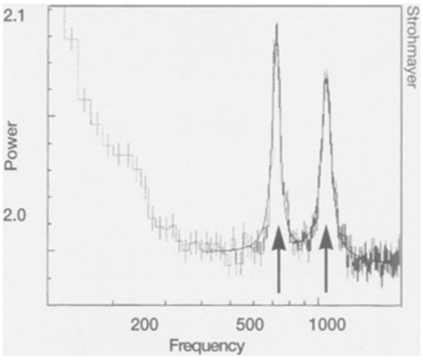
Observing the whirlwind of activity just above the surface of a neutron star hasn't been easy, however. By themselves, these dense bodies tend to keep a low profile. When in the company of other stars, however, their most violent behavior comes to light.

In a feeding frenzy, a neutron star's gravity pulls blobs of gas from its companion, gathering the gas into a swirling disk around itself, called an accretion disk. Gas at the inner edge of the disk orbits the neutron star at nearly the speed of light. Ultimately, the material spirals inward and crashes onto the dense star's surface. As it does so, it heats up and emits a stream of high-energy radiation, mostly X rays.

Spacecraft have observed X rays from the general vicinity of neutron stars for more than 30 years, but until recently, the radiation produced at or just above the surface had not been definitively measured. Theorists conjectured that such radiation, produced by blobs of gas that rapidly rotate in and out of view, might wax and wane in brightness every few thousandths of a second. Such fluctuations could hold important clues about the mass and size of the star, as well as its influence on surrounding space-time.

"If you were orbiting close to a neutron star, you would be orbiting 1,000 times a second, so to characterize what's going on, you have to have an instrument that can detect variations that occur 1,000 times a second," says M. Coleman Miller of the University of Chicago. Until recently, available detectors could not even begin to measure such rapid changes.

Slower oscillations—a few tens per second—in the brightness of X rays had been observed, but those frequencies probably relate to activity far from the stars' surfaces.



Strohmayer

A pair of quasiperiodic oscillations (arrows) in X-ray emissions from the neutron star system 4U 1728-34.

In late 1995, NASA launched the Rossi X-ray Timing Explorer (RXTE), designed to record rapid variations in X-ray brightness in neutron stars and black holes. Within 2 months, it had detected the most rapid oscillations ever identified from any astrophysical object.

To the surprise of many researchers, the oscillations in brightness exhibited by each neutron-star system occur at just a few specific frequencies. Rather than a cacophony of oscillations, astronomers have found that the "neutron stars are playing just a few cosmic chords, with two or three nearly pure tones," says Frederick K. Lamb of the University of Illinois at Urbana-Champaign. "The clockwork of the universe is much more orderly than we had dreamed."

That's a lucky break, says Miller, since it makes it easier to elucidate several properties of neutron stars and their influence on nearby matter.

The tones, or frequencies, aren't exact—from second to second they shift ever so slightly, which is why astronomers refer to them as quasiperiodic oscillations, or QPOs. About 18 of the neutron stars observed by the NASA craft show a pair of these oscillations. In most of these stars, the two QPO frequencies appear to be linked. If one of the oscillations slides up or down in frequency, the other shifts in the same direction by the same amount.

"X-ray astronomers are presently scrambling to try and make sense of [these paired oscillations]," notes van der Klis. Although researchers have yet to agree on an interpretation, "what is clear is that the rapid X-ray variability is directly linked with a neutron star's most distinguishing characteristic—its compactness, or density," he adds.

In a model proposed by Miller, Lamb, and Dimitrios Psaltis of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Mass., the pair of QPOs take on special meaning. The higher-frequency member of the pair, they suggest, has a simple interpretation. It is the frequency at which X-ray–emitting blobs of gas are orbiting the star, near the inner edge of the accretion disk.

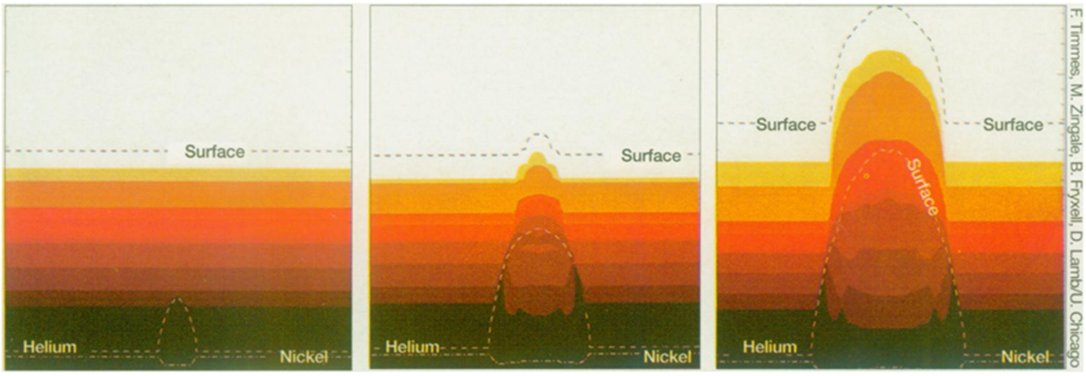
According to the researchers, the lower-frequency QPO is generated when radiation emitted by the rotating neutron star strikes the orbiting blobs of gas. To understand the interaction, it's important to note that the surface of the neutron star does not glow uniformly. Some of the gas that crashes onto the surface and generates the radiation is channeled by the star's magnetic field, falling only onto the magnetic poles. So the surface has hot spots, which rotate along with the star.

When the high-energy radiation from the hot spots runs into the glowing blobs of orbiting gas, it slows them down. As a result, the blobs spiral onto the star, increasing the intensity of the X rays.

Since the orbiting blobs of gas rotate at a different rate than the hot spots, the radiation emanating from the star does not usually collide with the blobs. It's the difference between these two rotation rates that determines when the radiation from the star will strike the orbiting gas, causing an upswing in X-ray emission. The researchers therefore contend that the lower-frequency QPO is in fact the difference between the rotation rate of the orbiting gas and the rate at which the neutron star spins.

The team's model suggests a way to test a key prediction of general relativity. At the same time, it provides a way to estimate the size of a neutron star.

According to Newton's theory of gravity, gas can orbit a compact star at any distance. But according to general relativity, if a star is massive enough and dense enough, it will warp



F. Timmes, M. Zingale, B. Fryxell, D. Lamb/U. Chicago

Simulation shows evolution of an X-ray burst emerging some 100 meters beneath the crust of a neutron star. Panels depict evolution of the burst at 6, 12, and 17 microseconds after the explosion that generates the intense radiation. Colors represent densities, with the densest material the darkest. Dashed lines track the regions of pure helium, which provides the fuel for the burst, and pure nickel, the final product of the burning. The hot spot is about 800 meters wide and covers about 1 percent of the surface area of the star.

space-time so strongly that the region just outside the star cannot possess a stable, circular orbit. Gas circling any closer than a certain minimum distance is doomed to crash onto the star's surface. This minimum distance is known as the innermost stable orbit.

Material residing closest to a neutron star orbits the fastest. Thus, gas in the innermost stable orbit has the highest possible orbital frequency.

Calculations by Miller, Lamb, and Psaltis indicate that orbiting gas produces X rays that brighten and dim at increasing frequency and intensity as it moves toward the neutron star—until the clumps of gas reach the innermost stable orbit. At that point, the frequency should stay the same even as the intensity of X rays striking the surface continues to rise.

Observations of the neutron-star system 4U 1820-30 appear to support this model. William Zhang, Tod E. Strohmayer, Alan P. Smale, and Jean H. Swank of NASA's Goddard Space Flight Center in Greenbelt, Md., recently observed the star for several months with RXTE. They found that as the intensity of the X rays rose and fell, so did the frequency of the X-ray oscillations. No matter how high the intensity, however, the frequency never rose above a ceiling of 1,050 times a second.

Their finding, reported in the June 20 Astrophysical Journal Letters, could be the first verification of general relativity in regions where space-time is strongly curved, says Lamb. "All previous tests of general relativity have been made in regions where space-time is curved only very, very weakly," he notes. If the evidence of an innermost stable orbit is confirmed, "it will be a major advance."

The finding also places an upper boundary on the size of this neutron star. Clearly, the radius of the star can be considerably smaller than the innermost stable orbit, but it cannot exceed that radius. In this case, that boundary is about 20 km.

Given the frequency of the innermost stable orbit and its radius, simple laws of physics provide a measure of the mass of the star. Following this prescription, that star has a mass about 2.2 times that of the sun, Miller says.

A neutron star this massive must have a rather stiff constitution. Otherwise, squeezed under the weight of gravity, it would collapse to form a black hole. The new observations appear to rule out models in which neutron stars are composed of relatively squishy material, such as a cluster of the elementary particles known as kaons or a soup of unconfined quarks.

In contrast, tightly packed ordinary nuclear material, such as neutrons, protons, and electrons, can withstand the pressure. Protons and neutrons are held in place by a force called the strong nuclear force. The new finding suggests that at small distances "the strong nuclear force is more repulsive than many nuclear physicists had expected," says Lamb.

Not all QPOs adhere to the model, cautions van der Klis. In the Oct. 20 Astrophysical Journal Letters, he and his colleagues, including Mariano Méndez of the University of Amsterdam and the National University of La Plata in Argentina, describe their observations of a neutron-star system called 4U 1608-52. The team finds evidence of a pair of QPOs, but in this system, the two frequencies behave in a puzzling fashion: When the lower frequency increases, the higher frequency follows suit, but at a slower rate, so the two peaks move closer together rather than maintaining a constant separation. Two or three other neutron-star systems show similar behavior, van der Klis says.

There's another way that astronomers are trying to unveil the true character of neutron stars. They are studying the brief flashes of radiation known as X-ray bursts. These are emitted hours to days after matter from a companion strikes the neutron star's surface.

The reason for the delay: As fresh material piles onto the star, it buries blobs that had arrived earlier, subjecting them to enormous temperatures and pressures. Eventually, conditions become so extreme that the nuclei of some of the buried material squeeze together. As low-mass nuclei merge to make carbon and heavier nuclei, they unleash enormous amounts of energy, igniting a thermonuclear explosion that releases a rush of X rays.

The explosion begins at one location just 100 meters beneath the crust, wherever the density and the temperature are highest, but it quickly spreads to engulf the entire surface. The global conflagration—and the X rays—continue until the reservoirs of nuclear fuel are exhausted and the surface cools.

Some astronomers have focused their attention on the first half-second or so of this process, when the explosion remains confined to a single locale. The X rays sweep past the viewer with each rotation of the neutron star. By observing this intermittent emission from the hot spot, astronomers are homing in on the mass and size of a neutron star.

Such determinations rely on a well-known consequence of general relativity: Gravity bends light. Even a relatively weak gravitational field, like that of the sun, can slightly distort the path of starlight that happens to pass nearby, making it seem as if the stars have shifted position.

The immensely more powerful gravity of a neutron star profoundly warps the travel path of the radiation emitted by a particular spot on the star. The bending is so strong that instead of shooting straight out into space, some of the X rays curve completely around the star, reaching an observer even when the spot is facing away from Earth. This light bending mutes the observed variations in the burst's intensity, since some X rays can be detected even when the spot has rotated out of view.

The strength of the gravitational field, and thus the amount of light bending, depends on the ratio of the mass of the neutron star to its radius. The more compact the star, the more strongly it bends light.

By comparing the variation in the intensity of the bursts as the star rotates and the intensity expected in the absence of light bending, researchers can estimate the ratio of the star's mass to its radius. Independent estimates of the radius of a neutron star may soon enable astronomers to measure its mass.

In the neutron-star system 4U 1636-536, Miller finds evidence for X-ray bursts that begin with two hot spots, on opposite sides of the neutron star. Such a configuration may enable astronomers to place even tighter limits on the maximum mass and radius of that star, he says.

As neutron stars continue to pull in matter with unrelenting force , they are giving up some of their best-kept secrets. ☐