Quasiperiodic oscillations probe galactic x-ray sources

"It's very frustrating," says William Priedhorsky, an x-ray astronomer at Los Alamos, "that the brightest x-ray sources in the sky are the ones we have had to be most speculative about." The sources of Priedhorsky's lament are the so-called galactic bulge sources, energetic enigmas found primarily in the galaxy's central bulge. Theorists had long speculated that the x-ray emissions of a bulge source originate from hot gas falling from a low-mass star onto the surface of its rapidly rotating neutron star companion. Unfortunately, evidence for this model had been indirect; the purported neutron star lies hidden beneath a plasma shroud. But recently the situation changed dramatically when a collaboration of researchers from the Max Planck Institute for Extraterrestrial Physics, the University of Amsterdam and MIT reported[1] observations of rapid, quasiperiodic x-ray oscillations from the bright bulge source GX5 − 1. Subsequent observations[2] of other bulge sources by Günter Hasinger (Max Planck Institute, Garching) and collaborators, and by Priedhorsky and John Middleditch (Los Alamos) have uncovered five more quasiperiodic oscillators. The existence of QPOs may provide astronomers with their first handle on the bulge source's neutron star. As a bonus they may also offer solutions to a few long-standing puzzles of galactic astronomy.

Several groups of astronomers had unsuccessfully looked for rapid, strictly periodic, x-ray pulsations that would betray the presence of a spinning neutron star at the heart of galactic bulge sources. In the spring of 1984 Walter Lewin of MIT sent a proposal to the European Space Agency to renew the search for rapid variability with the orbiting x-ray observatory Exosat. On 18 July 1984 Lewin and his European collaborators tried their luck, training the medium energy detectors aboard Exosat on GX5 − 1. In all, the group collected 1600 blocks of data—two seconds each, 15 seconds apart. Fourier transforms of the data then yielded a set of power spectra. The individual spectra were too noisy to allow meaningful study, but when the spectra were averaged, an unexpected feature emerged.

Instead of the sharp spike in the averaged power spectrum at the rotational frequency of the underlying neutron star, the astrophysicists observed a broad peak centered around 30 hertz. Further analysis of the peak revealed that GX5 − 1 oscillates with a frequency that varies in time, and that the frequency of these oscillations is strongly correlated with the fluctuating luminosity of the source. When the luminosity of GX5 − 1 increases by a factor of 1.4, the frequency of oscillations rises from 20 to 40 hertz. Hasinger and his collaborators analyzed observations of Cyg X-2 taken on 23 July and found that it, too, was a QPO; Priedhorsky and Middleditch discovered that Sco X-1, the brightest and best-studied x-ray source in the heavens, was a QPO as well. "Most people thought Sco X-1 had been studied to death," Fred Lamb (University of Illinois, Urbana–Champaign) said. "But now it shows us it still has some surprises left." By September QPOs had been found in three other bulge sources.

After learning of the existence of QPOs, other groups went back and took a look at their old data. Martin Weisskopf (Marshall Space Flight Center) found the tape on which the Einstein Observatory's observations of GX5 − 1 were stored. In a nearly textbook-perfect illustration of Murphy's law the tape containing the GX5 − 1 data—and the discovery of QPOs—had been misfiled in the Einstein archives. "To us it was just another source on a long list of sources," he says. But on analysis, Weisskopf and his colleagues confirmed Exosat's QPO. "Sometimes you win, sometimes you don't," Weisskopf observed philosophically.

Bulge sources. Many astronomers believed that bulge sources were close binary systems consisting of a neutron star locked in a gravitational dance with a star of around one solar mass. The low-mass stars in the brightest bulge sources are presumed to be in a giant phase, expanded beyond their Roche lobes, the hourglass-shaped surfaces past which particles cease to be gravitationally bound to either star in the binary pair. Matter from the envelope of the low-mass star is therefore free to fall toward the neutron star. As the matter falls, it is channeled through the neck of the hourglass, from which it emerges as a high-velocity jet into the gravitational well of the neutron star.

Conservation of angular momentum prevents the accreting matter from falling directly onto the surface of the neutron star. Instead, explains Jacob Shaham (Columbia University), "It swirls around the neutron star like water going down a drain. The reason for this swirling, in fact, is the same as the reason that water swirls down a drain. It must get rid of angular momentum. It forms an accretion disk, which is a way of carrying angular momentum out from a star while transferring plasma in."

If the neutron star did not have a magnetic field the accretion disk would swirl all the way to its surface. In the presence of a magnetic field, a standoff occurs when the stress of the accreting plasma is checked by the magnetic stress at the so-called Alfvén radius: Plasma outside the Alfvén radius orbits with the period determined by Kepler's laws; once inside, the plama must follow magnetic field lines.

When Shaham and M. Ali Alpar (Illinois) heard about the quasiperiodic oscillations of GX5 − 1 they immediately began to think about the Alfvén radius. They knew that as the accretion rate of matter onto the neutron star increases, the Alfvén radius contracts, and the Keplerian frequency of the plasma orbiting at that inner boundary to the accretion disk increases. Luminosity depends primarily on accretion rate; more matter falling onto the neutron star means more x rays. Alpar and Shaham were remind-

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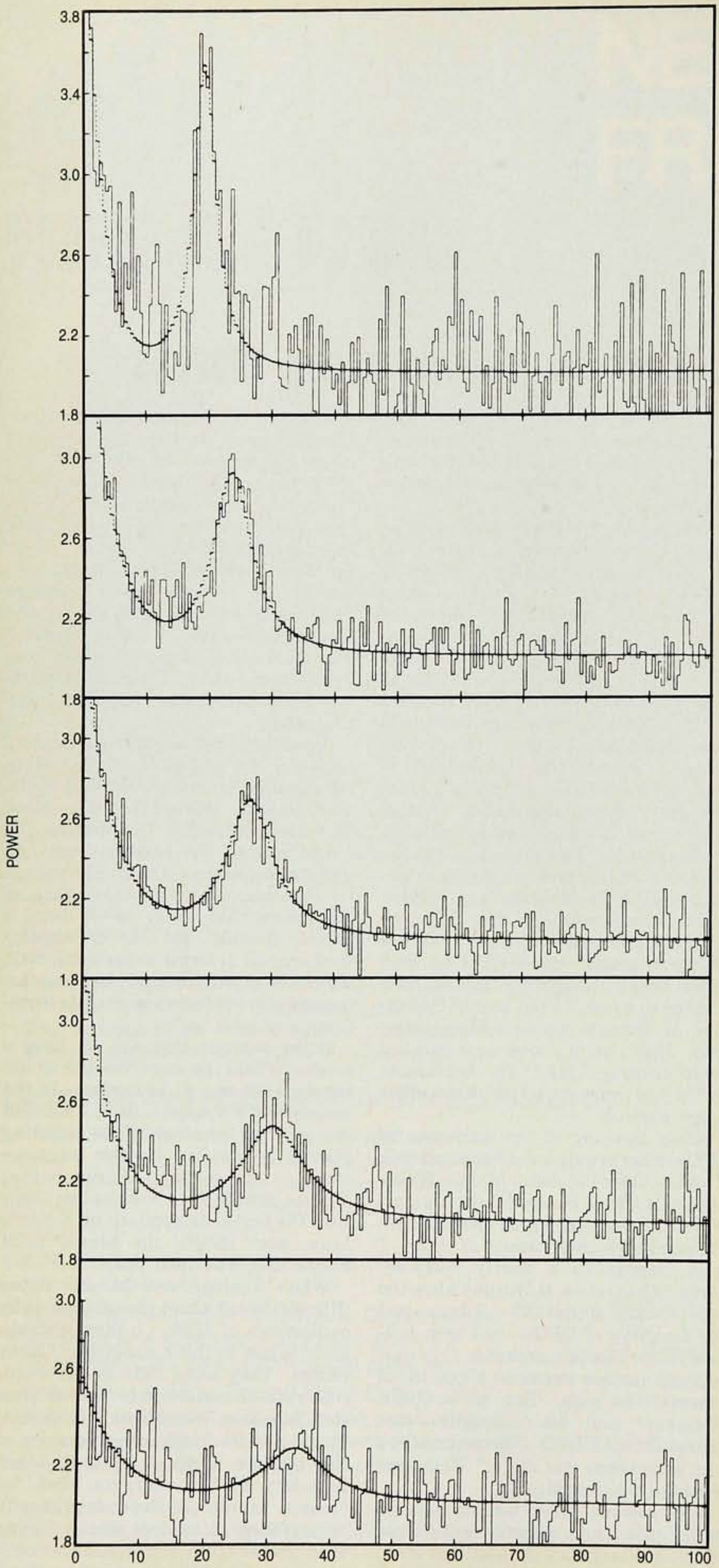


The first discovered QPO, GX5 − 1, demonstrates a striking correlation between oscillation frequency and source intensity. A linear display of the average power spectra of GX5 − 1 in six different source-intensity intervals, increasing from top to bottom, clearly shows how the source frequency increases with increasing intensity. this behavior led to the formulation of the beat frequency model.

ed of GX5 − 1, in which luminosity was strongly correlated with frequency. The two theorists quickly saw that the Exosat data could be explained[3] as the beat frequency between the orbital frequency of the plasma, the Alfvén radius and the rotational frequency of the neutron star.

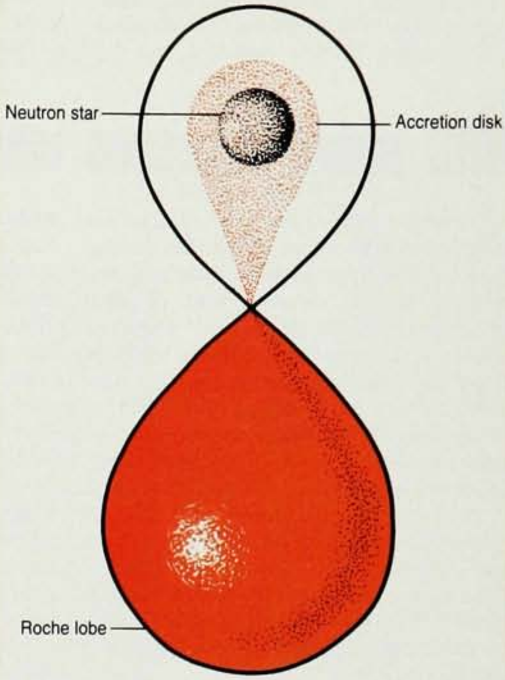
In the elaborated beat-frequency model of Fred Lamb, Noriaki Shibazaki (Illinois), Alpar and Shaham,[4] the plasma orbiting at the Alfvén radius is assumed to break up into clumps. Clumping can be caused by magnetic, thermal or shear instabilities: "You're always allowed to invoke clumpiness," explains Joseph Patterson (Columbia). An observer traveling along with one of these clumps would see the neutron star rotating below at an angular frequency that is just the difference between the actual spin rate of the neutron star and the Keplerian frequency of matter at the inner edge of the accretion disk. As inhomogeneities in the neutron star's magnetic field swing by, they strip plasma off the clumps, which then falls down the field lines to the surface of the neutron star. The matter plummets into the potential well of the star, accelerates, collides with the surface of the star, and emits a final, powerful burst of x rays.

Inhomogeneities in the magnetic field are almost guaranteed. If, for example, the neutron star is a magnetic dipole having its axis misaligned with the star's spin, the magnetic field will nibble at the clumps once or twice per turn (depending on the angle between the dipole axis and the rotation axis, and on the exact mechanism by which mass is drawn off the clumps). Pulses of x rays will therefore be observed at either the beat frequency or a harmonic, depending upon the geometry of the magnetic field.

Using their kinematic model, Alpar and Shaham estimated that the magnetic field of the neutron star in GX5 − 1 is of the order of 10^9 gauss—modest for neutron stars, which are created with magnetic fields of around 10^{12} gauss, but large compared to the Sun's surface field of around 1 gauss. The spin frequency of the neutron star is around 100 hertz. Both these numbers are happily close to what theorists had expected on the basis of the observed millisecond pulsars.

Millisecond pulsars. The first millisecond pulsar was discovered in November 1982 (PHYSICS TODAY, March 1983). Its frequency, around 630 hertz, was 20 times faster than that of the Crab pulsar, then the fastest spinning pulsar known. Measurements of the spin-down rate of millisecond pulsars show that they are very old and have magnetic fields of the order of 10^9 gauss. To explain this odd combination of extreme age and rapid spin, astrophysicists at the time proposed that the neutron star was spun up by matter accreting onto its surface. The model went on to predict that only low-mass x-ray binary systems—galactic-bulge sources—would give rise to millisecond pulsars. The reason for this is that a massive companion star evolves rapidly; it would transfer its mass too quickly to spin the neutron star, with its huge moment of inertia, up to its millisecond period. The observations of GX5 − 1 and Cyg X-2 apparently confirm this prediction.

The Roche lobe is an hourglass-shaped surface surrounding the stars in a binary system beyond which matter is not in the gravitational sway of either star. When the low-mass component of a galactic bulge source expands past the Roche lobe, its envelope swirls onto the neutron star, forming an accretion disk.



The existence of even a relatively weak neutron-star magnetic field may have important implications to the origin and evolution of the bulge sources. Observations of isolated pulsars show that neutron-star magnetic fields decay in just a few million years. But the low-mass stars in bulge sources are Population II stars, which were created along with the galaxy, about 10 billion years ago. "The systems that we thought for almost twenty years were very, very old neutron stars and therefore very likely to be without magnetic fields," Jonathan Grindlay (Harvard–Smithsonian Center for Astrophysics) says, "may now turn out to have appreciable magnetic fields. They are therefore not so old; they were relatively recently formed. That's a really interesting bit of general galactic astrophysics that we didn't have a clue to otherwise." Something must have recently happened to produce the neutron star, and that something was almost certainly the collapse of a white dwarf. Thus QPOs might prove that what has long been suspected is in fact going on: A white dwarf in an accreting binary system can collapse to form a neutron star without blowing itself to bits or disrupting the binary system.

This evolutionary scenario for bulge sources was noted in the paper announcing the discovery of QPOs in GX5 − 1 and quickly elaborated[5] in a paper by Lewin and Jan Van Paradijs. It carries with it an implication that is easily checked. Some bulge sources emit dramatic bursts of x rays. These bursts are interpreted as radiation from thermonuclear explosions triggered by the weight of matter slowly accreting from an unevolved, low-mass star—not a giant—onto the surface of a white dwarf. These explosions clear away the surface of the white dwarf, preventing the accumulation of enough matter to collapse it into a neutron star. So bursters should not contain neutron stars with the magnetic fields believed essential to generate QPOs. All data to date bear this model out: There appear to be two classes of galactic bulge sources, x-ray bursters and quasiperiodic oscillators.

Shaham is less convinced that the existence of a magnetic field implies that the neutron star is young. The magnetic field of a neutron star, he argues, can have two components. Currents circulating in the crust are probably the explanation for the neutron star's huge initial field; these would indeed decay rapidly. But a smaller field could come from currents in the superfluid protons in the core; these fields would have a much longer lifetime. A resolution to this question awaits further theoretical understanding of neutron stars.

Refinements. Meanwhile, some refinements to the beat-frequency model will undoubtedly be necessary. Sco X-1, unlike the other two QPOs, does not exhibit a neat correlation between frequency and luminosity. "Sco X-1 is just messier than the rest," Lamb says. As the source goes back and forth between quiescent and flaring states, dependence of frequency on luminosity varies in a way that suggests some form of hysteresis is taking place. Shaham is confident that this phenomenon can be explained by a more complicated topology of the accreting clumps and a better understanding of the interaction between the clumps and the neutron-star magnetic field.

To clinch unequivocally the beat-frequency model, however, the underlying period of the neutron star will have to be directly observed. The absence of evidence of the spin could be explained by the shrouding effect of the plasma surrounding the neutron star, together with the star's relatively weak magnetic field, which would not beam the x rays toward a distant observer. Another intriguing possibility is that the neutron star acts like a powerful gravitational lens that smears the pulses. At the Los Alamos workshop on astrophysics of time variability in x-ray and γ-ray sources, held the beginning of August in Taos, New Mexico, Hasinger showed extremely preliminary evidence for an underlying, fixed rotation frequency consistent with that predicted by the beat-frequency model.

Exosat is the only observatory from which the QPOs can be studied, and it will only be operational for about a year. During the fall, when the Earth is situated to make observations of the galactic bulge possible, the entire observing program of Exosat will be scrapped to search for and study QPOs. "There is no doubt that the Exosat discovery was a terrific thing," Shaham says. "They ought to be congratulated many thousands of times."

—BRUCE SCHECHTER

References

1. M. van der Klis, F. Jansen, J. van Paradijs, W. H. G. Lewin, E. P. J. van den Heuvel, J. E. Trümper, M. Sztajno, Nature **316**, 225 (1985).
2. G. Hassinger, A. Langmeir, M. Sztajno, J.

Trümper, Nature, in press (1985); W. Priedhorsky, J. Middleditch, IAU telegram 4060 (1985); L. Stella, IAU telegram 4102 (1985); W. H. G. Lewin, J. van der Klis, J. E. Trümper, IAU telegram 4101 (1985).
3. M. A. Alpar, J. Shaham, Nature **316**, 239 (1985).
4. F. K. Lamb, N. Shibazaki, M. A. Alpar, J. Shaham, Nature, in press (1985).
5. W. H. G. Lewin, J. van Paradijs, Astron. Astrophys. **149**, L27 (1985).

NRC panel assesses magnetic materials research

"The present separation in much of the magnetics community between fundamental and applied activities is detrimental to the development of new [magnetic] materials and applications.... This split manifests itself in departmental boundaries within universities as well as in professional conferences. Magnetic technology has now reached a level of sophistication where this gap [between physicists and engineers] must be closed...." This is one of several key conclusions drawn by the National Research Council's Committee on Magnetic Materials and cited in the report of their deliberations recently published[1] by the National Academy Press.

The committee, headed by Robert White of Control Data, was convened last year by the Materials Advisory Board of NRC at the request of the Defense Department. It was charged with assessing this country's current progress in magnetic materials research and development, identifying key problems that might limit the use of new magnetic materials, and recommending research and development areas likely to yield "the highest scientific and technological dividends within the next decade."

The study was initiated in response to a number of concerns: our increasing reliance on foreign sources for magnetic materials and devices; the declining interest in magnetic materials at US universities; Japan's commanding lead in new technological developments; and military and industrial concern that we may be "losing [our] dominance in a technology that plays a crucial role in the economy [and]... may provide a military advantage to the discoverer of new applications."

Despite the critical importance of magnetic materials, the report concludes, "the US is rapidly losing its competitive position." The committee attributes this slippage to the growing tendency of manufacturers to rely on foreign sources for magnetic components. In contrast to significant research investment abroad—Japan in particular—domestic manufacturers are finding it "difficult to economically justify significant expenditures on new technology."

Recommendations. Reminding us that "a large base of fundamental, exploratory research regularly produces unexpected, often useful results," the committee recommends that "an effort be made to regenerate a strong university-based program in magnetism and magnetic materials." With regard to condensed-matter physics, they cite: transition-metal magnetism, f-electron magnetic phenomena, and disordered magnetic systems. They also stress the need for better institutional mechanisms for coupling fundamental physics research to technolgy. "The advisory bodies... employed by NSF and other government agencies to evaluate [research] programs in magnetism [should] have some representation from applied centers [such as] those recently established at the University of California, San Diego and Carnegie–Mellon University, as well as from industry."

The report identifies three "growth areas" of particular technological promise:

▶ Permanent magnets. In the past decade the quality of permanent magnet materials has improved spectacularly with the introduction of cobalt–rare-earth compounds. However, the report points out, "the supply situation for cobalt is precarious." It was recently discovered that boron, iron and light rare earths form ternary compounds that exhibit magnetic properties superior to the cobalt–rare-earth compounds. The research issue, we are told, is to understand the origin of these good magnetic properties, and how they can be further improved.

▶ Soft magnetic materials "offer enormous opportunity for improvement," particularly through the introduction of amorphous materials. Such materials might, for example, replace those currently used in magnetic recording heads. The recording density of present-day heads is limited by their low saturation magnetizations. Research in this area must address such questions as stability and controllability of domains.

▶ Magnetic recording, the committee concludes, offers "enormous opportunity for innovative research." Increased storage density is crucial if we are to benefit fully from the increasing component densities on semiconductor chips. Better understanding of the magnetic and nonmagnetic properties of particulate and thin-film media will allow tapes and disks "to be designed rather than developed empirically, as is done today."

Fundamental questions. In connection with its recommendation that "the relationships between scientific research in magnetism and magnetics technology be strengthened," the report cites several examples of "fundamental problems whose solutions would advance magnetic technologies":

▶ Surfaces. By what mechanism does a surfactant increase the coercivity of a magnetic particle? Why are the magnetic properties of amorphous films more surface sensitive than their crystalline counterparts?

▶ Fundamental limits. How could one increase magneto-optic or magnetoresistive coefficients by an order of magnitude? Could one design a useful ferromagnetic insulator in which the sublattices are all ferromagnetically coupled?

▶ Statistical physics. What governs the spread in the nucleation fields for an ensemble of magnetic particles?

▶ Amorphous materials. What governs their formation? What is the origin of their anisotropy and magnetorestriction?

▶ Micromagnetics. Much remains to be learned about the dynamics of magnetic domain wall singularities such as Bloch lines. "We believe that the United States has overreacted in its disenchantment with magnetic bubbles by abandoning all fundamental research in this area."

To "bring the two cultures together," funding agencies should look more favorably on proposals involving the collaboration of physicists, engineers and materials scientists, the committee recommends. Such interdisciplinary activity should also be supported by interdepartmental courses at universities, travel grants and tutorial sessions at national conferences.

The report's final recommendation urges the formation of a national resource center for the assimilation of magnetic materials information. Pointing out that more and more information is making its first appearance in the Japanese literature, the committee strongly endorses the recent decision of the IEEE Magnetics Society to publish translations from the Japanese journals, and it urges more effort in this direction.

—Bertram Schwarzschild

Reference

1. *Magnetic Materials*, Publication NMAB-426, National Academy, Washington, D.C. (1985). ☐