PERSPECTIVES: ASTROPHYSICS

Signs of Extreme Gravity

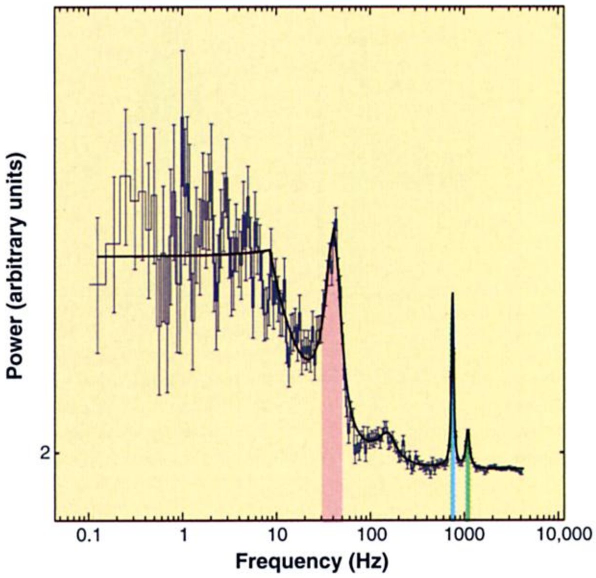
Sharon Morsink

Neutron stars are created in the cores of massive stars during supernova explosions (*1*). The central core of a neutron star can be many times denser than nuclear matter, well beyond the highest densities accessible to terrestrial experiments, but they do not collapse to form a black hole. Strong magnetic fields and superfluid and superconducting interiors contribute to the fascination these stars hold for many physicists. But for the gravitational physicist, the most exciting aspect of a neutron star is its strong gravitational field, second only to that of a black hole. The estimated strength of a neutron star's gravitational field is so large that Einstein's theory of general relativity manifests itself, leading to several observable effects that do not occur in classical gravity. Observations of neutron stars may thus provide a rare glimpse of the strong-field regime of gravity.

The Rossi X-ray Timing Explorer (RXTE) satellite, which has been observing neutron stars and black holes in binary systems since 1995, is our best tool at present for observing these gravitational effects (*2*). When matter is transferred from the normal star to the neutron star or black hole in a binary, x-rays are emitted. RXTE can detect variations in x-ray luminosity at time scales down to a fraction of a millisecond. This enables the satellite to measure the frequencies at which the luminosity from a source is changing. Recently, oscillation frequencies on the order of 1 kilohertz (kHz) have been detected (*3*) in the Fourier spectra of neutron stars and black hole candidates. The importance of this observation can be understood by considering the circular motion of a particle around a neutron star (or black hole). For a neutron star with typical mass and an orbit as close as possible to the star, the orbital frequency of the particle is on the order of 1 kHz. This means that if the recent observations are indeed related to the orbital motion of matter near a neutron star, the radiation originates in a region with a very strong gravitational field and may bear the signature of relativistic effects.

Kilohertz frequency oscillations have been observed for more than 20 sources. Two types of oscillations have been seen. The first is seen during type I x-ray bursts, which are believed to occur when sufficient hydrogen has been accreted on the surface of a neutron star for the nuclear fusion to occur, resulting in a short burst of x-rays. As long as there exists some inhomogeneity, the light from the burst will vary as the star spins, resulting in a peak in the Fourier spectrum at the frequency with which the star spins. Spin frequencies inferred from the bursts range from 330 to 590 hertz (Hz) for different sources (*3*, *4*). If the latter frequency is indeed the spin frequency of a neutron star, it would be the third fastest neutron star known today (*5*).

The second type of kilohertz oscillation appears in the persistent emission from the stars. For example, the Fourier spectrum for the neutron star binary system 4U 1728-34 shows broad peaks corresponding to quasi-periodic oscillations (QPOs) (see the first figure) (*6*), instead of the sharp spikes seen in the case of strictly periodic phenomena. Three QPO peaks can be identified, whose frequencies are shifted to higher frequencies in later spectra (data not shown). The blue and green peaks move at about the same rate, and the difference between them was initially believed to be constant. This constant frequency was the same as the star's spin frequency inferred from x-ray bursts and has been interpreted in terms of a beat frequency model (*7*).



Mysterious peaks I. This Fourier spectrum of the neutron binary star system 4U 1728-34 shows three distinct quasi-periodic peaks (*6*). Note that the frequencies read off this figure do not correspond to a frequency of light but instead to the frequency at which the light is flickering. Reproduced from the original data.

The beat frequency description of x-ray signals from neutron stars is similar to the beat phenomenon in music. A guitarist tunes a guitar by plucking two different strings such that both strings should produce the same pitch. If the strings are out of tune, their vibration frequencies will be slightly different. Our ears interpret this by combining the two tones. The combined tone is at a pitch that averages the two pitches; the intensity of the average pitch varies periodically with time. The variation in intensity is called a beat, and the frequency of the beat is the difference between the frequencies of the two strings. The essence behind a beat frequency model is that the system has two fundamental frequencies, whose combination creates a beat frequency that is the difference between the two fundamentals.

In such a model, the green peak may correspond to the orbital frequency of matter at the inner edge of an accretion disk and the blue peak to the difference between the orbital frequency and the star's spin frequency. As the inner edge of the disk moves radially inward, the orbital frequency increases according to Kepler's law. Later observations have shown, however, that the difference between the two high-frequency peaks is not constant, although the spin frequency and the green-blue difference never differ by more than 25% (*3*). This clearly contradicts the prediction of the beat frequency model, indicating that the model is either incorrect or requires additional physics.

If the green peak can indeed be interpreted as an orbital frequency, it would represent a constraint on the (unknown) mass and radius for the neutron star (*7*). The orbital radius corresponding to the highest observed frequency must be larger than the star's radius or its innermost stable circular orbit. The highest frequency peak observed to date is 1329 hertz (*8*), which may be high enough to place constraints on theories of dense nuclear matter.

The red peak's frequency increases as the square of the green's. This scaling behavior could be a result of the frame-dragging effect of general relativity, which arises from the distortions of space-time caused by the rotating mass and causes the orbital plane to precess if it is tilted with respect to the star's equator. It has been suggested that the red peak corresponds to the precession frequency of tilted orbits in the inner edge of the disk (*9*). Subse-

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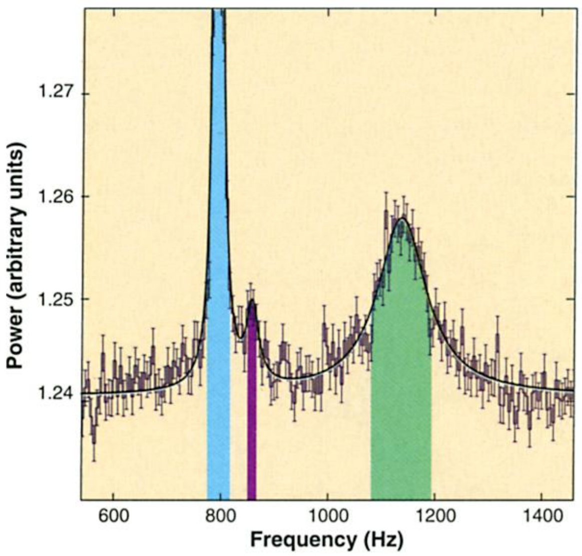
quent observations (*6*) have shown, however, that the red frequencies are sometimes two and sometimes four times the precession frequencies predicted by general relativity. The symmetry of the system makes it likely that the observed frequency should be double the theoretical, but a quadrupled frequency is difficult to explain. Several other models for the QPO peaks have been proposed; the issue remains to be resolved (*3*).



Mysterious peaks II. An additional peak has appeared between the green and the blue peaks (*10*). This spectrum of 4U 1728-34 was measured at a different time than the first figure, and the frequencies of the QPOs will therefore not match exactly.

Another kilohertz QPO (colored purple in the second figure) has recently been discovered for several sources alongside the familiar blue and green QPO peaks through the use of new data analysis techniques (*10*). It has been suggested (*10*) that the new peak is produced by the same mechanism as the low-frequency red peak. If the two peaks have a common origin, the purple peak should be a beat frequency between the red and blue peaks. In this case, blue plus red should equal purple, but there is a mismatch of about 20 Hz. This suggests that the red and purple peaks are either independent or are caused by similar phenomena at different radii in the disk (*10*).

The frequency difference between the purple and blue peaks is constant in time, suggesting that the purple feature is a beat corresponding to another beat with unknown frequency. In this case, another beat should appear on the other side of the blue peak. This was not seen in two of the sources that were studied but was observed in a third source (*10*), strengthening the case for interpreting the new peak as a beat. It remains unclear, however, how the beats are produced and why the lower lobe is absent in two of the sources. It has been suggested in the popular press (but not in a refereed publication) that frame dragging may again be responsible. This seems unlikely, because the theoretical frame-dragging rate (*11*) for 4U 1728-34 should be no more than 20 hertz, whereas the purple-minus-blue frequency is 65 hertz.

The new data are intriguing but also raise many questions. The beat features have so far only appeared in low-luminosity sources. Do they also appear in high-luminosity sources? Black hole candidate sources show QPOs that may be similar to the blue and red peaks (although they appear at lower frequencies). Does a beat feature appear in these spectra? And is the peak separation between the purple and blue sources really constant? More data will help answer some of these questions, but it will be difficult for theorists to provide an explanation for the QPO phenomena. It is clear, however, that the x-rays originate from a region with a strong gravitational field and that in these neutron star systems general relativity will be an important effect, which is rare in astronomy.

References and Notes

1. "Imagine the Universe" has lots of information about neutron stars. See http://imagine.gsfc.nasa.gov/.
2. The Web site for the RXTE satellite is http://guinan.gsfc.nasa.gov/docs/xte/. See also http://guinan.gsfc.nasa.gov/docs/xte/learning_center/.
3. M. Van Der Klis, *Annu. Rev. Astron. Astrophys.*, in press.
4. L. Bildsten, T. Strohmayer, *Phys. Today* **52** (no. 4), 40 (1999).
5. The most common type of neutron star observed is a pulsar, which emits constant, steady pulses, as opposed to the intermittent pulses seen in the stars discussed here. The fastest pulsars, called millisecond pulsars, are believed to be spun up to their fast speeds by the accretion of material from an orbiting companion in an x-ray binary system. It is thus very important that the RXTE observations have shown neutron stars in x-ray binaries to have spin periods similar to the millisecond pulsars. A "missing link" neutron star with characteristics typical of both the accreting x-ray binaries and the millisecond pulsars has also recently been observed [R. Wijnands and M. Van Der Klis, *Nature* **394**, 344 (1998)].
6. E. C. Ford, M. Van Der Klis, *Astrophys. J.* **506**, L39 (1998).
7. M. C. Miller, F. K. Lamb, D. Psaltis, *Astrophys. J.* **508**, 791 (1998).
8. S. van Straaten *et al.*, *Astrophys. J.* **540**, 1049 (2000).
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10. P. G. Jonker, M. Mendez, M. van der Klis, *Astrophys. J.* **540**, L29 (2000).
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PERSPECTIVES: AIDS

Boosting Immunity to HIV—Can the Virus Help?

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The human immunodeficiency virus (HIV), the cause of AIDS, invades certain types of host immune cells, in particular $CD4^+$ T helper 1 (T_H1) lymphocytes that are progressively eliminated as the virus replicates. These $CD4^+$ T cells, along with $CD8^+$ cytotoxic T lymphocytes, are essential for mounting a coordinated immune attack against HIV. In the absence of antiretroviral drug therapy, the intensity and diversity of $CD4^+$ and $CD8^+$ T cell responses against HIV increase as the amount of virus in the blood (viral load) decreases during primary HIV infection (*1*, *2*). Treating newly infected HIV patients with antiretroviral triple drug therapy (HAART) provides a rapid reduction in the initial burst of virus replication and helps to preserve the HIV-specific $CD4^+$ T_H1 cell population from rapid elimination (*2*); unfortunately, this strategy also lessens the intensity of the HIV-specific $CD8^+$ cytotoxic T cell response (*3*). This calls into question the actual benefit of early therapeutic intervention, which does not completely eradicate the virus and leaves the patient with an incomplete antiviral immune response. In an effort to solve this dilemma, researchers have interrupted drug treatment during primary (acute) HIV infection. Although the benefits of such therapeutic manipulations remain controversial, anecdotal evidence from patients who have had drug therapy interrupted suggests that periodic and transient increases in the viral load restimulate the waning HIV-specific $CD8^+$ cytotoxic T cell response (*4*, *5*). Now, in a recent issue of *Nature*, Walker and co-workers (*6*) report that administering HAART to patients within 72 hours of diagnosing HIV infection, and then discontinuing treatment after 1 to 2 years, helps to establish durable immune control of the virus.

Walker and colleagues treated eight acutely infected HIV patients with HAART, and then, after complete suppression of the viral load for at least a year, interrupted drug therapy. Before treatment was stopped, the $CD4^+$ T_H1 (but not $CD8^+$ cytotoxic T cell) response to HIV could be detected in all eight patients. After discontinuing treatment, the virus rebounded and

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