New Views of Neutron Stars

Satellites launched in the last ten years have proved to be powerful new tools for studying these compact stellar remnants. With them, astronomers have found remarkable new phenomena and solved several old mysteries.

Lars Bildsten and Tod Strohmayer

Born amid the violence of supernova explosions, neutron stars are the extremely dense endpoints of stars that initially had a mass of more than about 8–10 $M_\odot$ ($M_\odot$ is the mass of the Sun, about 2×10^{33} g). During its final collapse, such a star expels most of its material, leaving behind a remnant—a neutron star—packing a typical mass of 1.4 $M_\odot$ into a radius of only 10 km.[1] With a density comparable to that of an atomic nucleus, a neutron star provides an extreme environment for fast and violent phenomena: Matter orbiting a neutron star can have a period as short as a millisecond; when it crashes into the star (that is, when it is "accreted"), this matter can be moving at one-third the speed of light. Because their behavior can vary over readily observable timescales, neutron stars can be rich sources of information about nuclear physics, general relativity and astrophysics.

Though elusive, neutron stars have been detected and studied over an amazingly broad range of electromagnetic frequencies, from the radio to GeV gamma rays. To date, astronomers have found more than a thousand of the roughly 10^8 neutron stars thought to be present in our galaxy. There has been rapid growth recently in our knowledge of neutron stars, thanks largely to new orbiting astronomical satellites. Much of the progress, summarized in this article, has come in our understanding of accreting neutron stars and of "soft gamma-ray repeaters," neutron stars that undergo sudden large energy releases.

The existing picture

With no internal fuel left to be burned, neutron stars must tap alternative energy sources if they are to be visible. The first unambiguous detection of neutron stars occurred 30 years ago with the discovery of radio pulsars. These neutron stars lose their rotational energy in a textbook example of electromagnetism. A star rotating at angular frequency $\Omega = 2\pi/P_s$, with its magnetic moment μ misaligned from the spin axis by an angle θ, radiates energy at the rate of

$$\frac{dE}{dt} = -\frac{2\mu^2\,\Omega^4 \sin^2\theta}{3c^3} = -\frac{B_p^2\,R^6\,\Omega^4 \sin^2\theta}{6c^3}, \qquad (1)$$

where c is the speed of light, B_p is the magnetic field strength (in gauss, where $1\ \mathrm{G} = 10^{-4}$ T) at the magnetic pole and R is the stellar radius.[2]

Although most neutron stars have been discovered as radio pulsars, only a small fraction of the radiated energy (typically about 10^{-5}) actually goes into radio emission. Much of the energy instead departs as photons with energies above 100 MeV. (See the article by Donald Backer and Shrinivas Kulkarni in PHYSICS TODAY, March 1990, page 26.)

As a radio pulsar radiates away its rotational energy, its spin frequency decreases: $\dot{E} = I\Omega\dot{\Omega}$. The rate of change of a star's rotation, $\dot{\Omega}$, is of fundamental observational importance. From such measurements, researchers have estimated (using equation 1) the magnetic field of radio pulsars to be 10^8–10^{12} G. The precise timing of radio pulsars has also yielded astonishing astronomical discoveries,[3] such as multiple Earth-mass planets orbiting a neutron star and the direct confirmation of the loss of orbital angular momentum due to gravitational radiation in the double neutron star binary PSR 1913+16—for which Russell Hulse and Joseph Taylor (Princeton University) received the 1993 Nobel Prize.

The depth of a neutron star's gravitational potential well makes accretion of material another prime energy source for the star. Matter slamming into a star of mass M releases approximately GM/R, or about 200 MeV, per accreted baryon—much greater than the energy available from nuclear fusion (about 7 MeV per baryon). The brightest accreting neutron stars reside in binary systems and accrete matter from their companions, either by tidally stripping material from their surface or by gathering up some of the wind they expel (see figure 1). These accreting neutron stars have luminosities more than a thousand times that of the Sun, for a typical mass accretion rate of $\dot{M} \approx 10^{-9}\,M_\odot$/yr. Much of this released energy is thermalized before leaving the star; the inferred surface temperature of 10^7 K is consistent with the typical photon energies that give these systems their name, x-ray binaries. (X-ray binary systems can also contain black holes.)

A neutron star's accreting matter often comes from a surrounding accretion disk. The disk itself is rotating, so that the accreted material adds angular momentum to the neutron star. Thus, unlike radio pulsars, which are spinning down, accreting neutron stars in x-ray binaries should spin up as time passes.

Astronomers recognize two broad classes of x-ray binaries, depending on whether the mass-providing star is massive or not.[4] High-mass x-ray binaries (HMXBs) typically have donor masses of greater than 5 $M_\odot$, whereas low-mass x-ray binaries (LMXBs) have donor masses of less than 1 $M_\odot$. Neutron stars in HMXBs usually have polar magnetic fields of $B_p \sim 10^{12}$ G, which are strong enough to funnel the accreting matter onto the magnetic poles. X rays are produced at the poles when the gravitational potential energy is released, and, because the magnetic moment is generally not aligned with the axis of rotation, these stars appear as x-ray pulsars: We observe x-ray pulses as the star's rotation takes the magnetic poles in and out of our line of sight.[2] In contrast, the neutron stars in LMXBs do not show any evidence of dipolar accretion and so must have magnetic fields that are orders of magnitude weaker—much less than 10^{10} G.

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FIGURE 1. AN ACCRETION-POWERED MILLISECOND PULSAR. This rendering from an animation sequence (http://universe.gsfc.nasa.gov/videos/millisecond.html) shows an accreting neutron star binary system thought to resemble the first-known accreting millisecond pulsar, SAX J1808.4–3658. The neutron star is surrounded by an accretion disk fed by material from the low-mass companion star. The powerful accretion-driven x-ray flux from the neutron star is ablating the surface of its companion. Such ablation is thought to be the cause of a 2% modulation at the orbital period in the x-ray flux from the SAX pulsar. (Courtesy NASA/GSFC: W. Feimer/Allied Signal.)

The origin of this clear observational magnetic distinction between HMXB and LMXB neutron stars is not known. Several conjectures have been made, and in many of them a star's age is a key factor. Since more massive stars live shorter lives, the neutron stars in HMXBs are characteristically much younger than those in LMXBs—10^7 years compared to 10^9 years—and have accreted less matter. Thus, many researchers have speculated that the neutron stars in LMXBs have been around long enough for their magnetic fields to have either decayed ohmically or been "buried" as material has accreted.

A puzzle solved in HMXBs

Our most direct knowledge of the interplay between a neutron star's magnetic field and accretion comes from the accreting x-ray pulsars found in HMXBs. These highly magnetized neutron stars typically rotate with periods of 1–1000 s. The small moments of inertia of these stars make it possible to measure accretion torques directly by observing changes in their spin frequencies. The early picture of the spin evolution of accreting pulsars, however, was based on infrequent measurements of only a few stars. Those observations sometimes yielded torque estimates a factor of 100 lower than simple physical estimates. In addition, some neutron stars were found to undergo short episodes of spinning down, indicating that angular momentum was actually being lost while the star was accreting. Physical reasoning tells us that the torque from accretion should spin up a magnetic star until the star's rotation period nearly matches the orbital period of accreting matter just outside its magnetosphere—the region where the stellar magnetic field dominates the accretion flow.[5] (It is the presumption that most x-ray pulsars are near this spin equilibrium that permits the inference that their magnetic fields are typically in excess of 10^{12} G.) These arguments, however, don't tell us what happens once a star reaches spin equilibrium; on this important point, we have had to wait for new observations.

A project initiated by John Grunsfeld and Tom Prince (Caltech), Mark Finger and Bob Wilson (NASA's Marshall Space Flight Center) and their colleagues in the early 1990s used the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma-Ray Observatory to observe many x-ray pulsars. The continuous observations made by this all-sky monitor (which is primarily a gamma-ray burst detector) provided the frequent torque measurements, on timescales ranging from days to years, that were needed to resolve the mystery. With BATSE, Deepto Chakrabarty (MIT) and his colleagues found that when the 7.6 s pulsar 4U 1626–67 started spinning down in 1991 after nearly 20 years of spinning up, the decelerating and accelerating torques, though opposite in sign, were nearly equal in magnitude. Another prime example of this behavior, shown in figure 2, is found in the BATSE data for the 4.8 s pulsar Cen X-3, which exhibits intervals of 10–100 days of steady spin-up and spin-down, again with nearly equal torques. The frequent transitions in the torque produce a much slower long-term spin-up rate.

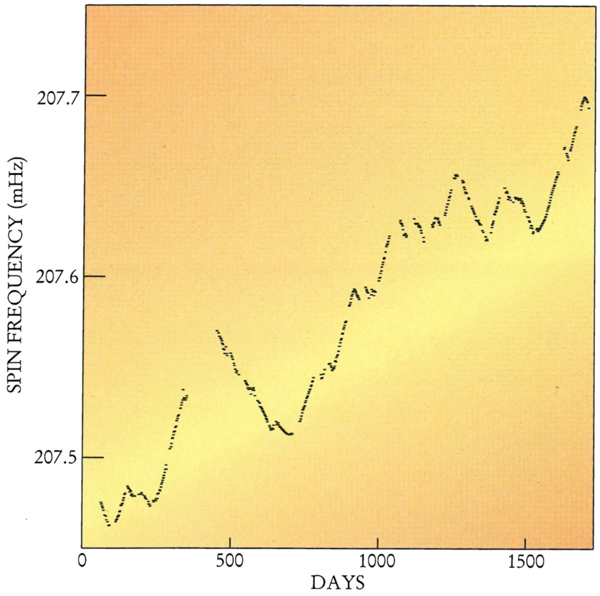

FIGURE 2. SPIN FREQUENCY MEASUREMENTS of the accreting x-ray pulsar Cen X-3, made with the Burst and Transient Source Experiment on the orbiting Compton Gamma Ray Observatory over a period of four and a half years. The spin evolution is dominated by torque reversals on timescales of 10–100 days. The magnitudes of the spin-up and spin-down torques (the slopes of the curve) are very similar, and they agree quantitatively with estimates from simple magnetic accretion theory. The long-term averaged spin-up rate is much lower. (Courtesy M. Finger.)

From observations such as these, we now know that these alternations are a rather common occurrence.[6] Difficulties in explaining this phenomenon in terms of the commonly accepted theories led Kazuo Makishima (University of Tokyo) and his coworkers and later Robert Nelson (now at Princeton University) and his collaborators to speculate that the accretion disk was alternating its sense of rotation, becoming retrograde at times. Though a radical hypothesis, this notion may be just what is needed.

Finding the elusive spin in LMXBs

With no observable pulsations from neutron stars in LMXBs, their spins have been very difficult to find. The stars have very likely been accreting long enough to gather up about $0.1\,M_\odot$ of new material, however, and the angular momentum transferred to a neutron star from this much accretion can spin up the star to millisecond periods when the stellar magnetic field is weaker than about 10^9 G. Backer (University of California, Berkeley) and his colleagues found the first such rapidly spinning neutron star, a millisecond radio pulsar, in 1982. Many millisecond radio pulsars were subsequently found in binary systems, and their very small spin-down rates suggest weak surface magnetic fields of 10^8–10^9 G. Therefore, many believe that these millisecond radio pulsars were once the neutron stars of LMXBs, spun-up by since-discontinued accretion.[7] To prove this claim, numerous astronomers have searched for millisecond rotation periods in LMXB neutron stars, but only recently is evidence emerging.

In addition to their more persistent, accretion-powered x-ray emission, neutron stars in LMXBs show brief bursts of x rays. These bursts are caused by unstable thermonuclear reactions in the accreted layer of hydrogen and helium on the neutron star (see the box below). Although nuclear reactions release a small amount of energy compared to accretion, these bursts are very bright: The fuel accumulated over a few hours is burned in only 10 s. Theoretical investigations suggest that the instability that starts the thermonuclear flash probably begins at a localized site and then spreads around the star, eventually burning all the nuclear fuel.[8]

Because these bursts rise to a peak luminosity in about 1 s (see figure 3) and cover much of the stellar surface, the burning front must race along at a speed of at least 10 km/s. A conductive deflagration front would be orders of magnitude too slow to burn the whole star in a few seconds. Most thermonuclear bursts, however, are energetic enough to initiate convection, which seriously alters the situation. Bruce Fryxell (Goddard Space Flight Center) and Stan Woosley (University of California, Santa Cruz) first argued that a convective front can move at a speed fast

Thermonuclear Instabilities on Accreting Neutron Stars

Not long after x-ray bursts were first observed, it was realized that their origin was the unstable thermonuclear ignition of matter accumulated on neutron stars. Due to a thermal instability discovered by Carl Hansen (JILA) and Hugh Van Horn (University of Rochester), stars are unable to burn the accreted matter as fast as it accretes. Instead, they accumulate hydrogen and helium for hours or days and then burn the fuel in about 1–10 s. At the accretion rates of observed neutron stars, the atmospheric temperature always exceeds 10^7 K, and hydrogen burns through the carbon-nitrogen-oxygen cycle. The process is limited, however, by the beta-decay lifetimes of oxygen-14 and oxygen-15, and at the densities of the catalysts (10^{-3} that of hydrogen), it takes a few days to burn all of the hydrogen. In that time, however, the accreted fuel will have been compressed to high enough densities ($\rho > 10^5$ g/cm^3) and temperatures ($T > 10^8$ K) to ignite the helium. Thus the helium burns before the hydrogen is consumed.[4,8]

The helium burning, producing carbon through the triple-α process, is very temperature sensitive. Only for temperatures above 5×10^8 K is the burning stable; at lower temperatures, any thermal perturbation leads to thermal runaway. Such a temperature requires a very high local accretion rate that is most often realized at the magnetic poles of the accreting pulsars. There, the strong funneling of the accretion onto the poles and the local confinement of the accretion mound (at least until ignition) most often results in stable burning.[17] For this reason, thermonuclear x-ray bursts are not seen from x-ray pulsars. Only recently has an exception been found—the SAX pulsar (see main text).

All of the observed regular x-ray bursting neutron stars accrete at $\dot{M} < 10^{-9}\,M_\odot/\mathrm{yr}$ and show no evidence of magnetic fields strong enough to focus the accretion onto an area small enough to stabilize the burning. The thermonuclear instability forces the star to burn the fuel in a time-dependent manner—the fuel accumulates for a few hours until the instability sets in, and then the fuel is burned in the ensuing 10 s when the temperature typically exceeds 10^9 K. The burning processes are quite complicated: Most of the hydrogen is burned in a series of rapid proton captures followed by beta decays of the heavy nuclei—the "rp-process."[18] Modeling the burning requires knowledge of the thermonuclear reaction rates for nuclei far on the proton-rich side of the valley of stability, but most of these rates have not been experimentally measured.

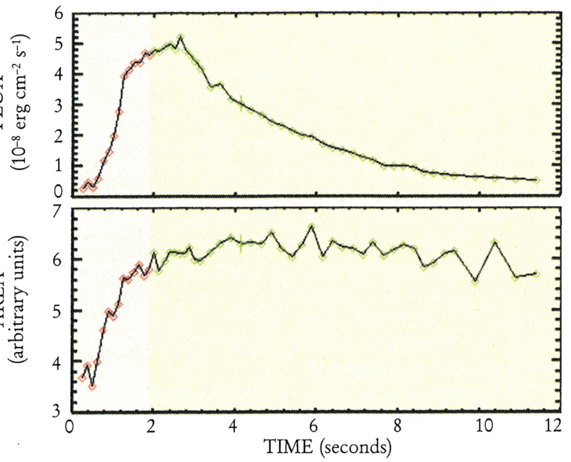

FIGURE 3. A THERMONUCLEAR X-RAY BURST from the neutron star in the low-mass x-ray binary 4U 1728–34, as observed with the Proportional Counter Array onboard the Rossi X-Ray Timing Explorer. The x-ray flux (top panel) shows a rapid rise (red) of 1–2 s, followed by a slower decay (green). For blackbody radiation from a sphere, the emitting surface area is proportional to F/T^4, where F and T are the flux and temperature, respectively. The increase in the inferred emitting area (bottom panel) during the rise of the burst provides strong evidence that the nuclear burning front is spreading over the surface of the star. As the decay begins, the burning has engulfed the entire surface, and the emitting area remains essentially constant as the flux drops. Representative error bars are shown.

enough to ignite the entire surface in a few seconds.[8]

Spurred by the detection of a 7.6 Hz oscillation during one burst, Robert Schoelkopf (Caltech) and Richard Kelley (Goddard Space Flight Center) suggested that, during these x-ray bursts, the long-sought LMXB neutron star spin might finally be observed, either during the initial rise, when the thermonuclear instability is well localized, or later during the burst if only a fraction of the stellar surface is burning.[8] With this hope, astronomers eagerly awaited the launch of the Rossi X-Ray Timing Explorer (RXTE) in late 1995. Named in honor of Bruno Rossi of MIT, one of the American pioneers of x-ray astronomy, RXTE carries instruments with both large collecting areas and high time resolution to study the submillisecond dynamical timescales of neutron stars and stellar-mass black holes. The Proportional Counter Array (PCA) on RXTE, the largest x-ray detector yet flown, can time the arrival of x rays with microsecond accuracy, making it uniquely capable of searching for millisecond rotation periods.

In April 1996, Strohmayer and his colleagues reported the discovery of 363 Hz (2.75 ms) pulsations during some of the x-ray bursts from the neutron star in the LMXB 4U 1728–34.[9] The strongest pulsations were seen on the rising portions of bursts, which suggested that the pulsations came from the rotation of a thermonuclear hotspot on the star. In addition, a remarkable feature was seen in the persistent accretion-driven x-ray emission from 4U

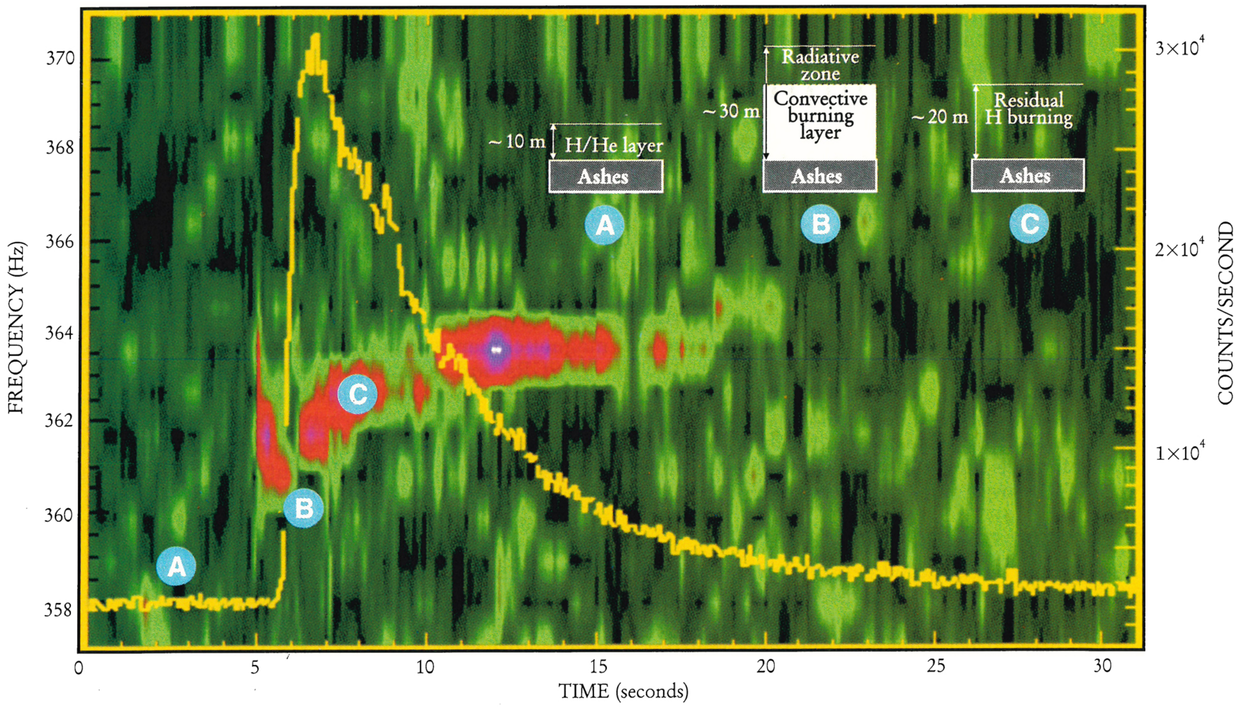

FIGURE 4. FREQUENCY DRIFTS OF ABOUT 2 Hz are seen in the millisecond pulsations during an x-ray burst from the neutron star 4U 1728–34. The color image shows the Fourier power spectrum of the pulsations as a function of time through the burst. The overlaid profile is the x-ray flux during the burst, which shows that the pulsations (in red) begin as the burst rises to its peak. The inset schematics A, B and C depict the behavior during the burst of the surface layer where the thermonuclear burning occurs. Before the burst, the accumulated hydrogen/helium layer is roughly 10 m thick. During the burst, it expands to triple its thickness, and a well-defined boundary develops between the inner convective and the outer radiative layers. At this time, because of angular momentum conservation, the pulsation frequency is the lowest. After about one second, the burning has covered the star and the convection halts. As the energy from the nuclear flash is radiated away and the remaining hydrogen burns, the layer cools and contracts, and the frequency approaches its maximum—thought to be the spin frequency of the bulk of the neutron star.

1728–34: a pair of high-frequency quasi-periodic oscillations (QPOs), including one with a frequency above 1000 Hz. QPOs are variations in the x-ray flux that have a preferred frequency but are not strictly coherent pulsations, and they show up as relatively broad peaks in the Fourier spectra of time series data. QPOs had previously been seen only up to 50 Hz in neutron star fluxes. The frequencies of the QPOs in 4U 1728–34 changed with accretion rate, but maintained a nearly fixed difference frequency of about 363 Hz—the frequency seen during the bursts.

These facts led Strohmayer and his colleagues to propose that the frequency seen during bursts is the spin frequency of the star, and that the QPO frequency separation results from beating between the spin frequency and the orbital frequency of accreting material very near the stellar surface. Observations of many LMXBs with RXTE over the last two years have shown that kilohertz QPO signals are very common in those systems and might prove to constrain the properties of nuclear matter at high densities.[10]

So far, x-ray bursts with millisecond pulsations have been observed from six different neutron stars. The observed frequencies range from 330 to 590 Hz, a range very similar to the spin frequencies of millisecond radio pulsars. The asymptotic frequencies at the ends of the bursts are stable to better than 1 part in 10^4 per year, indicating that they are determined by stable clocks, such as rotation. The most puzzling observation is that the pulse frequency increases by 1–2 Hz during the cooling tail of many bursts (see figure 4).

What causes this increase in frequency? The torque required to change a neutron star's spin frequency by even a few percent over a few seconds is enormous, and cannot be produced by an x-ray burst. Drifting in the location of the burning front could affect the frequency, but should result in frequency decreases as often as increases. A more likely explanation is simply angular momentum conservation. A burst's initial thermonuclear flash heats the burning region to 10^9 K and causes it to expand outward by about 20 m. If the burning shell can decouple from the bulk of the neutron star and spin on its own, which is possible if the magnetic field is not too strong, angular momentum conservation forces a modest decrease in the rotation frequency of the decoupled layer. The predicted decrease is about 1.5 Hz for the neutron star in 4U 1728–34. The observed frequency is lowest when the atmosphere is most extended, just after the burst onset. As the layer cools and the atmosphere subsides, the rotation frequency increases, and eventually the layer settles back into corotation with the neutron star. That this phenomenon is so easily explained in terms of rotation increases our confidence that the spin frequencies of neutron stars in LMXBs are finally being measured.

The first accreting millisecond pulsar

The x-ray observations of millisecond periods during thermonuclear bursts provided strong evidence for the rapidly rotating neutron stars thought to reside in LMXBs. However, we still had little direct evidence that these neutron stars are magnetized at all—if they were, magnetic channeling of the accretion flows would produce pulses in their accretion-powered emission as their magnetic axes sweep across our line of sight. This picture suddenly changed in April 1998, when Rudy Wijnands and Michiel van der Klis (University of Amsterdam) discovered the first accretion-powered millisecond pulsar with RXTE.[11] The neutron star SAX J1808.4–3658, previously identified as a thermonuclear x-ray burster by the Italian–Dutch satellite BeppoSAX, was found to have brightened to detectable levels when RXTE serendipitously slewed across its position in the sky. Subsequent observations revealed 401 Hz pulsations in the persistent x-ray flux. A naive application of magnetic accretion theory puts the surface field in the range of (2–8) $\times 10^8$ G, just like the millisecond radio pulsars!

Chakrabarty and Edward Morgan (MIT) measured a highly compact 2 h neutron star orbit from the observed Doppler shifts in the pulsations, and they inferred[10] that the mass of the companion star was 0.05–0.15 $M_\odot$. They also discovered a 2% modulation of the x-ray flux at the orbital period, which they conjectured was produced by scattering from a wind driven from the companion by direct irradiation from the neutron star (see figure 1). In combination with its companion's small implied mass, this neutron star is then very similar to millisecond radio pulsars in binaries, which also appear to be actively ablating their companions.

With the discoveries of millisecond periods during x-ray bursts and the 401 Hz accreting pulsar, there is now little doubt that the accreting neutron stars in many LMXBs are rotating with millisecond periods. Some of them may be magnetized enough to become millisecond radio pulsars once accretion shuts off. Many important questions remain unanswered, however, the most important being, Why don't all LMXBs show persistent pulsations?

Soft gamma-ray repeaters

So far, we have discussed three energy sources that can make neutron stars detectable: rotation, gravitational energy release from accretion, and thermonuclear fusion. Another possible source is the stellar magnetic field. From equation 1 above and a simple estimate of the energy density in the dipolar magnetic field, it can be determined that, in a pulsar that is spinning down, the magnetic energy will dominate the rotational energy after the passage of a time

$$t \approx 10^3\ \mathrm{yr} \left(\frac{M}{1.4\, M_\odot}\right)^2 \left(\frac{B_p}{2\times 10^{14}\ \mathrm{G}}\right)^{-4} \left(\frac{R}{10\ \mathrm{km}}\right)^{-5}.$$

So, if the magnetic field is strong enough, the magnetic energy can dominate after less than 1000 years. Recent discoveries of pulsating x-ray sources associated with soft gamma-ray repeaters (SGRs), which are rare sources of repetitive bursts of 10–100 keV photons, indicate that some neutron stars may in fact be this strongly magnetized. Whether such a star can turn some of its stored magnetic energy into radiation remains open to debate.

SGRs are a separate population from the classic gamma-ray bursters (described by Neil Gehrels and Jacques Paul in PHYSICS TODAY, February 1998, page 26). SGRs have several distinguishing characteristics: a shorter burst duration, of about 0.1 s; a "softer" gamma-ray spectrum with fewer high-energy photons; and a Galactic space distribution (three out of the four known SGRs are in the plane of our galaxy). What is more, the bursts repeat!

The puzzle of the SGRs began with an extremely energetic gamma-ray burst detected by a number of space observatories on 5 March 1979 from the direction of the supernova remnant N49 in the Large Magellanic Cloud. This unique burst is known to astronomers simply as "the March 5th event." It began with an extremely bright, short-duration gamma-ray pulse with a spectrum extending to high energies, similar to most gamma-ray bursts. It then evolved to a softer, weaker emission with an 8 s pulsation—the spin of the neutron star was suspected as the culprit. A few weaker bursts were detected later from the same sky position, showing that the source of the March 5th event could produce repetitive outbursts. Two similar sources of repetitive bursts were discovered over the next 15 years. The bursts' gamma-ray energies and

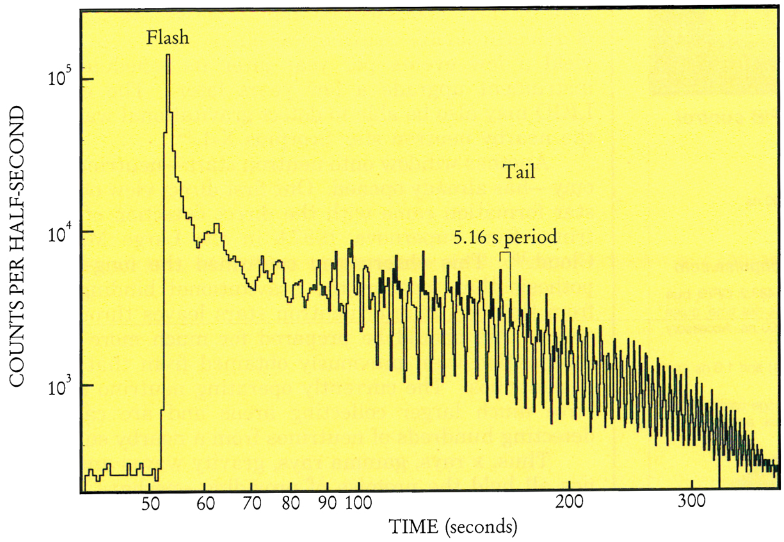

FIGURE 5. THE TREMENDOUS GAMMA- and x-ray flare observed on 27 August 1998 from the magnetar SGR 1900+14, as recorded by the gamma-ray burst detector aboard the Ulysses spacecraft. The intensity and time are both shown on a logarithmic scale. The strong "ringing" 5.16 s pulsations are clearly evident in the decaying tail of the flare. (Courtesy K. Hurley.)

enormous fluxes with millisecond timescale variability all suggested that the origins of these events were neutron stars.

The discovery of magnetars

Motivated by the enormous energy release of the March 5th event and the 8 s pulsation, Robert Duncan (University of Texas at Austin) and Christopher Thompson (University of North Carolina) rather boldly claimed[12] that the SGRs were not only neutron stars but also highly magnetic, with a surface field exceeding 10^{14} G. The two researchers argued that such powerful fields in these neutron stars—dubbed "magnetars"—could provide the energy source for SGR bursts, as well as provide a way to spin down the neutron star to a leisurely 8 s period in only 5000–10 000 years (see equation 1). Bohdan Paczynski (Princeton University) pointed out another effect of such strong fields: Because the Landau level spacing in such a field greatly exceeds the thermal energy, the scattering opacities of the electrons in the stellar atmosphere would be greatly suppressed, thereby allowing the huge luminosities—seven orders of magnitude larger than the Sun's—observed from SGR bursts.

The suspicions that SGRs are neutron stars were confirmed in 1993 when radio observations by Kulkarni (Caltech) and Dale Frail (National Radio Astronomy Observatory) revealed[13] that the most prolific SGR burst source, SGR 1806–20, was associated with the young supernova remnant G10.0–0.3. Later x-ray observations found a pointlike x-ray source at the same location. Subsequently, the location of the March 5th event was also shown to coincide with a faint x-ray source in the supernova remnant N49.

The magnetar hypothesis also has been confirmed, and again observations with RXTE provided the breakthrough. In November 1996, BATSE detected a new outburst from SGR 1806–20, and over the next two weeks observations were performed with RXTE. When Chryssa Kouveliotou (Marshall Space Flight Center) and Strohmayer pooled their data, they not only discovered 7.5 s pulsations in the quiescent x-ray flux from SGR 1806–20, but found that the neutron star was spinning down at a very rapid rate.[14] Their findings from the RXTE data, combined with archival data obtained with Japan's Advanced Satellite for Cosmology and Astrophysics (ASCA) in October 1993, showed a long-term increase in the spin period of about 8×10^{-11} s/s, which suggests a spin-down age of 8000 years and a magnetic field strength of 2×10^{14} G. This is one of the highest magnetic fields inferred for a neutron star and strongly supports the notion that some neutron stars are born with surface fields greater than 10^{14} G. Estimates of the number and ages of SGRs in the Galaxy suggest that the magnetar birthrate may be as much as one-tenth that of normal radio pulsars.

Discoveries providing additional support for the existence of magnetars continue to be made. Last year, Kevin Hurley (University of California, Berkeley) and his collaborators reported the discovery with ASCA of 5.16 s pulsations from SGR 1900+14. Subsequent RXTE observations by Kouveliotou and coworkers confirmed the detection and found that this SGR source is also slowing rapidly. Then, on 27 August 1998, the astronomical community witnessed an enormous burst from SGR 1900+14 that showed strong 5.16 s pulsations following the initial flash of gamma rays (figure 5). This event was very similar to the March 5th event and produced the highest peak and integrated energy fluxes ever observed from a cosmic source; during the flare the ionization rates in Earth's night ionosphere reached daytime levels!

The future of neutron star research

The last ten years have seen enormous growth in our understanding of neutron stars and how they manifest themselves in various astrophysical settings. Although this article emphasizes the opening of the millisecond window onto neutron stars made possible with the advent of RXTE, comparable discoveries may well be in store for radio pulsars with the newly upgraded Arecibo Observatory in Puerto Rico and other ground-based radio and optical work.

There is every reason to believe that new classes of neutron stars will be discovered by continued observations from the currently orbiting satellites combined with the international fleet of new x-ray and gamma-ray satellites planned for launch over the next two years. This fleet includes the American Unconventional Stellar Aspect (USA) x-ray timing instrument, the American Advanced X-Ray Astrophysics Facility—recently renamed the Chandra X-Ray Observatory in honor of the late theoretical astrophysicist Subrahmanyan Chandrasekhar—and the German Broadband Imaging X-Ray All-Sky Survey (ABRIXAS) this spring; the European X-Ray Multi-Mirror Mission (XMM) and the Japanese–American Astro-E high-resolution x-ray spectroscopy mission in early 2000; and the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) in 2001. The spectral capabilities of these instruments may even finally provide a direct measurement of the expected gravitational redshift from the surface of a neutron star, either with a gamma-ray line or an atomic transition in the soft x-rays.

There are also completely new windows on neutron stars about to open. The Laser Interferometer Gravitational Wave Observatory (LIGO), which will begin taking data in early 2002, will be able to detect the coalescence of a nearby double neutron star binary system, and should yield a few events per year after its scheduled major instrument upgrade a few years later. The enhanced LIGO may also be able to detect gravitational waves from the nearby neutron star Scorpius X-1.[15]

Another window onto neutron stars—neutrino astronomy—has already opened. Our first direct view of neutron star formation came with the direct detection of 20 neutrinos from supernova 1987A in the Large Magellanic Cloud.[16] This observation confirmed the long-held hypothesis that most of the gravitational binding energy from the formation of neutron stars leaves through neutrinos. We should be prepared for much more detailed information than previously obtained from that handful of neutrinos. The currently operating neutrino detectors have much larger collecting areas and are capable of detecting hundreds of neutrinos from a nearby supernova.

Thus, x rays, gamma rays, gravity waves and neutrinos all hold the promise of providing—perhaps in just a few years—still newer views of neutron stars.

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