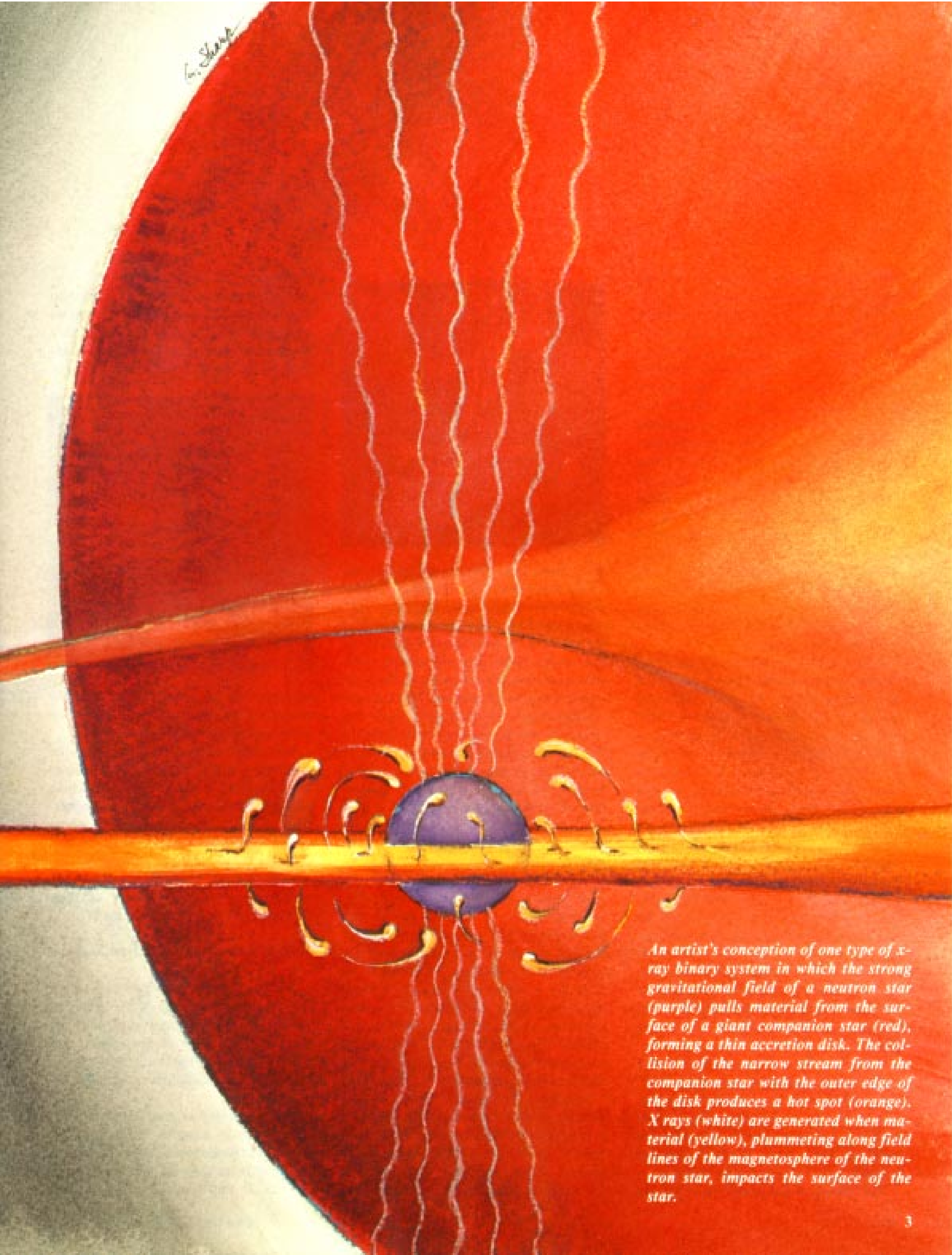
X-Ray Variability in astrophysics

A report on the *Workshop on Astrophysics of Time Variability in X-Ray and Gamma-Ray Sources*, held in Taos, New Mexico, August 5-9, 1985.

by Richard I. Epstein, Frederick K. Lamb, and William C. Priedhorsky



An artist's conception of one type of x-ray binary system in which the strong gravitational field of a neutron star (purple) pulls material from the surface of a giant companion star (red), forming a thin accretion disk. The collision of the narrow stream from the companion star with the outer edge of the disk produces a hot spot (orange). X rays (white) are generated when material (yellow), plummeting along field lines of the magnetosphere of the neutron star, impacts the surface of the star.

Study of the variability of x-ray and gamma-ray sources is a relatively mature field. providing astrophysicists with a wealth of information about the workings of binary stellar systems and the internal structure of the component stars. Recently, interest in these rapidly changing systems has soared as a result of new data gathered by the European Space Agency's satellite EXOSAT, launched in 1983. EXOSAT has been able to gather invaluable data on rapid and repeating transients as well as on periodic behavior and more subtle effects such as frequent, small shifts in the period of an oscillatory phenomenon. Orbital periods and partial eclipses in binary systems, x-ray bursts. and even changes in the direction of flow of accreting matter onto neutron stars are among the new details that can now be studied.

Until recently, luck has been a big factor in discovering transient behavior. But that will change when the new Japanese ASTRO-C satellite is launched in 1987 and the new American XTE satellite is launched in the early 1990s (see "The Next Generation of Satellites"). The plan is to equip these satellites with all-sky sensors that will be able to discover and monitor transient behavior anywhere in the sky. In addition, the satellites will carry large-area detectors that will allow the spectral and temporal behavior of cosmic x-ray sources to be studied with unprecedented precision. Moreover, the satellites will be specially designed so that observers can quickly turn the large-area detectors toward sources showing unusual behavior. Both the quantity and quality of information about transient systems should therefore increase dramatically in the coming years.

It was thus felt that the summer of 1985 would be an opportune time for a workshop to review the accomplishments of the last decade, to discuss plans for the new satellites, and to prepare for the expected wave of new, more detailed data on variable x-ray and gamma-ray sources.

The timing of the workshop could not

have been more fortunate. During the weeks preceding the workshop, unexpected new results from EXOSAT kept pouring in, requiring repeated overhaul of the schedule to accommodate reports on two newly discovered phenomena. One was quasiperiodic oscillations in the x-ray output of some neutron-star binaries (see "Quasiperiodic Oscillations"); these oscillations provide the first direct probe of the transition region between the neutron star and the accretion disk present in these systems. The other was evidence that the famous neutron star in Hercules X-1 (Her X-1) is freely processing, which could explain the origin of its enigmatic 35-day cycle (see "Her X-1: Another Window on Neutron-Star Structure").

In view of the importance and controversial nature of the evidence on Her X-1, a special effort was made to gather for the first time those scientists with major interest in the 35-day cycle. Almost all were able to attend the workshop, making possible in-depth discussions of the dramatic new evidence for precession in this system. It became apparent that several possible stumbling blocks to acceptance of this interpretation could be set aside.

Similarly, the workshop was the first meeting at which almost all the scientists involved in the discovery and interpretation of quasiperiodic oscillations were present. Participants stayed up late into the night, discussing the new data and arguing over its interpretation.

Many commented that the workshop was one of the most exciting scientific meetings they had ever attended. Not only did the workshop pave the way for planning use of the next generation of x-ray

Workshop Photos by LeRoy Sanchez

satellites, but it served as a forum for discussing the startling discoveries being made with present instruments.

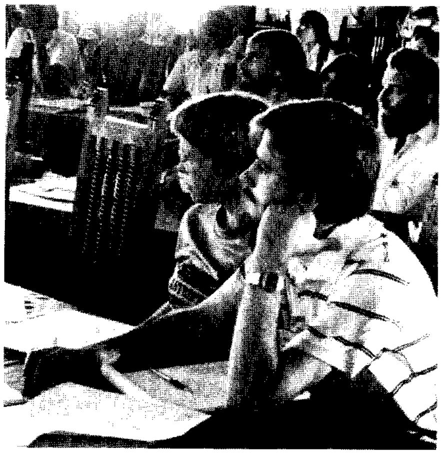
This report summarizes many of the discoveries and developments discussed in the sessions of the workshop, to which all participants contributed. The illustrations and tables arc adapted from material presented at the workshop. The selection of topics and the views expressed arc obviously those of the authors alone. The participants and the subjects of their scheduled talks are listed on page 37.

X-Ray Astronomy and Sco X-1

The brightest stellar x-ray source in our sky, Scorpius X-l (Sco X-1), has been studied since the beginning of x-ray astronomy. The story of this object, discovered early but not easily understood, illustrates the development of x-ray astronomy,

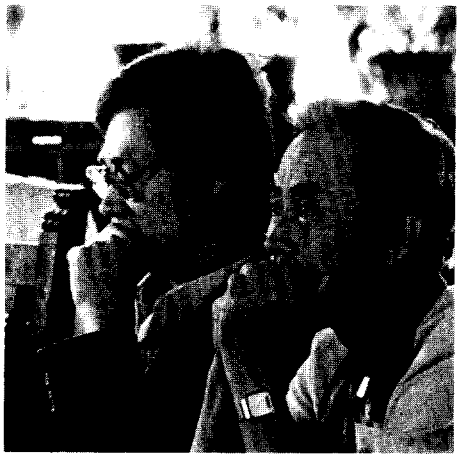
Sco X-1 shines so intensely that it delivers to earth about a thousand x-ray photons per square centimeter per second, ten times more than the next brightest x-ray star, It was detected during a 1962 rocket experiment led by Riccardo Giacconi that was designed to look for solar x rays scattered from the moon. The discovery of such a bright x-ray source outside the solar system came as a great surprise. Sco X-1 was found to radiate x rays with ten thousand times the total power of our sun.

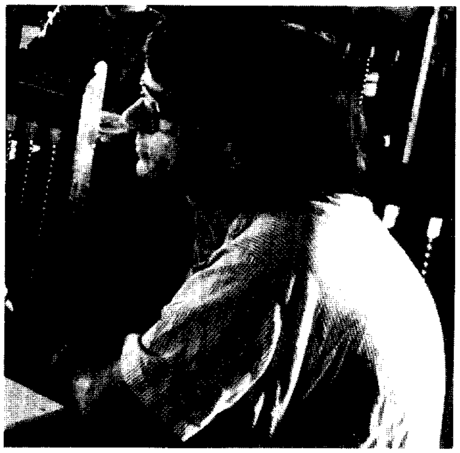
What sort of object could be such a powerful source of x rays? One suggestion was that Sco X-1 is a neutron-star system in which matter is heated to millions of degrees as it falls into the enormous gravitational potential of the neutron star, producing x rays. Without direct evidence of a neutron star in Sco X-1, this accretion model remained highly speculative until the early 1970s when similar but pulsed x-ray sources were discovered. The rapid



regular pulsing of these sources signaled the presence of a rotating magnetic neutron star. Many of these pulsed x-ray sources were found to be neutron-star binaries in which a close companion star is the source of the accreting matter. Although Sco X- I exhibits no strong x-ray pulsations. regular variations in the Doppler shifts of its spectral lines and in the brightness of its optical light, discovered in 1975, show that it too has a companion—one that circles it every 0.787 days.

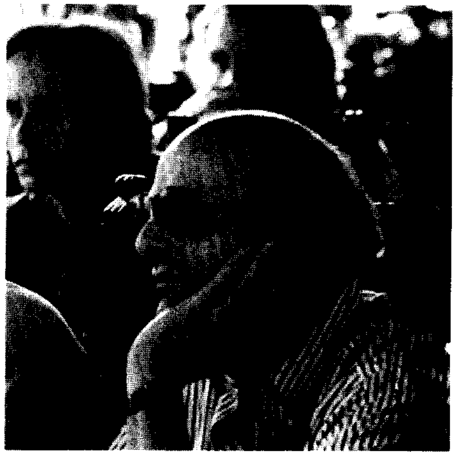
Sco X-1 has revealed its nature only grudgingly. The system is too small and far away for its components to be resolved:





what little we know is deduced from the shapes of its x-ray and optical spectra and their variations with time. For example, the existence of an accretion disk around the neutron star in Sco X-1 was confirmed by the discovery in 1981 of simultaneous rapid changes in the optical and x-ray intensity. The lack of delay between the two signals meant that the x rays are generating optical light in an accretion disk near the neutron star as opposed to generating optical light by traveling to and heating the companion star.

Even an old friend can surprise you. Sco X-1 did just that early in 1985 when it was shown to exhibit quasiperiodic oscillations in its x-ray intensity. This phenomenon is a variation of several per cent in the x-ray output that is not perfectly periodic,



that is, the period of the intensity variation also varies. As a result, the Fourier transform of intensity squared versus time, namely, the power-density spectrum, gives a broad rather than a sharp peak. The centroids of the observed peaks lie in the region of the spectrum between 6 and 50 cycles per second (Hz). The cause of the oscillations cannot be simply rotation of the neutron star—-a very precise clock—but could be produced by interaction of the magnetosphere of the neutron star with the surrounding disk—a sloppy clock. These quasiperiodic oscillations are the first direct evidence of what is happening near the neutron star and confirm our expectations that study of x-ray variability will reveal the detailed dynamics of these binary systems.

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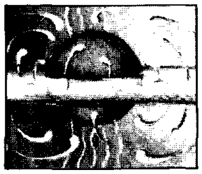

The Next Generation of Satellites

Within the next few years two planned satellites, one Japanese and one American, should begin gathering data vital to a deeper understanding of x-ray sources and their variability, The instruments aboard the satellites will allow both detection of previously invisible sources and much more detailed studies of bright sources.

The Japanese satellite, ASTRO-C (Fig. 1), which is being designed by the Japanese Institute of Space and Astronautical Science, will be launched in 1987. Its key instrument will be a proportional counter, called the large-area counter (LAC), with an effective area of 0.45 square meter. A proportional counter, the workhorse of x-ray astronomy, was chosen as the main instrument because it can be made with a large effective area, is rugged, and has good background rejection. It has moderate spectral resolution ($\Delta E/E \sim 0.2$). Signals from extraneous sources and the diffuse glow of the x-ray sky will be excluded with mechanical vanes that restrict the field of view to 0.8 by 1.7 degrees. The LAC will be sensitive to energies from 1.5 to 30 keV, a range that includes most of the output of neutron-star x-ray sources,

NASA'S X-Ray Timing Explorer (XTE) (Fig, 2) will be larger than ASTRO-C and is planned to be launched from the Space Shuttle in the 1990s. Its kcy instrument will be a proportional counter array composed of eight separate detectors with a total effective area of a full square meter, The individual fields of view of the eight detectors will typically be nearly coaligned, but it will be possible for observers to command two detectors to an offset position to permit simultaneous observations of source and background intensititcs. This feature will make it possible to separate variations in faint or weakly varying x-ray sources from variations in the background. The field of view will be similar to that of ASTRO-C, but the use of xenon rather than an argon-xenon mixture will allow detection of higher energy x rays (2 to 60 kcV).

XTE will also carry a large-area (0.2-square-meter) hard x-ray telescope sensitive to energies from 20 to 200 kcV and pointed in the same direction as the proportional counter. In combination with the proportional counter array, this instrument will allow simultaneous spectral and variability measurements over the entire energy range from 2 to 200 keV. This capability will make possible detailed study of a host of kcy phenomena, such as the spectra of transient x-ray sources, cyclotron features in accretion-powered pulsars, the energy output from active galactic nuclei, and changes in the state of' certain galactic sources, such as the black-hole candidate Cygnus X-1.

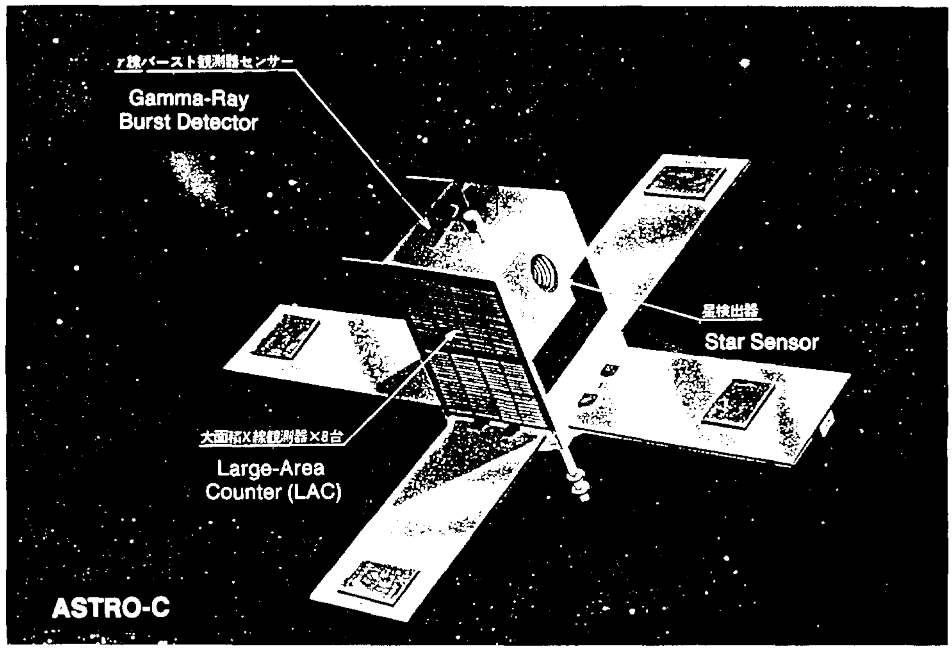

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Fig. 2. ASTRO-C, Japan's third x-ray astronomy satellite. The large-area counter (LAC) will consist of eight proportional counters containing a mixture of argon (70%), xenon (25%), and carbon dioxide (5%) and will be sensitive to x rays with energies from 1.5 to 30 keV. The gamma-ray burst detector will be a two-detector system: a 60-square-centimeter NaI(Tl) scintillation counter sensitive to photon energies from 15 to 480 keV and a 100-square-centimeter proportional counter sensitive to the same photon energies as the LAC. The all-sky monitor (out of view on the side opposite the LAC) will consist of two proportional counters. Also shown is the star sensor used to determine the orientation of the satellite.

The square-meter class of detector on the two satellites will allow the study of

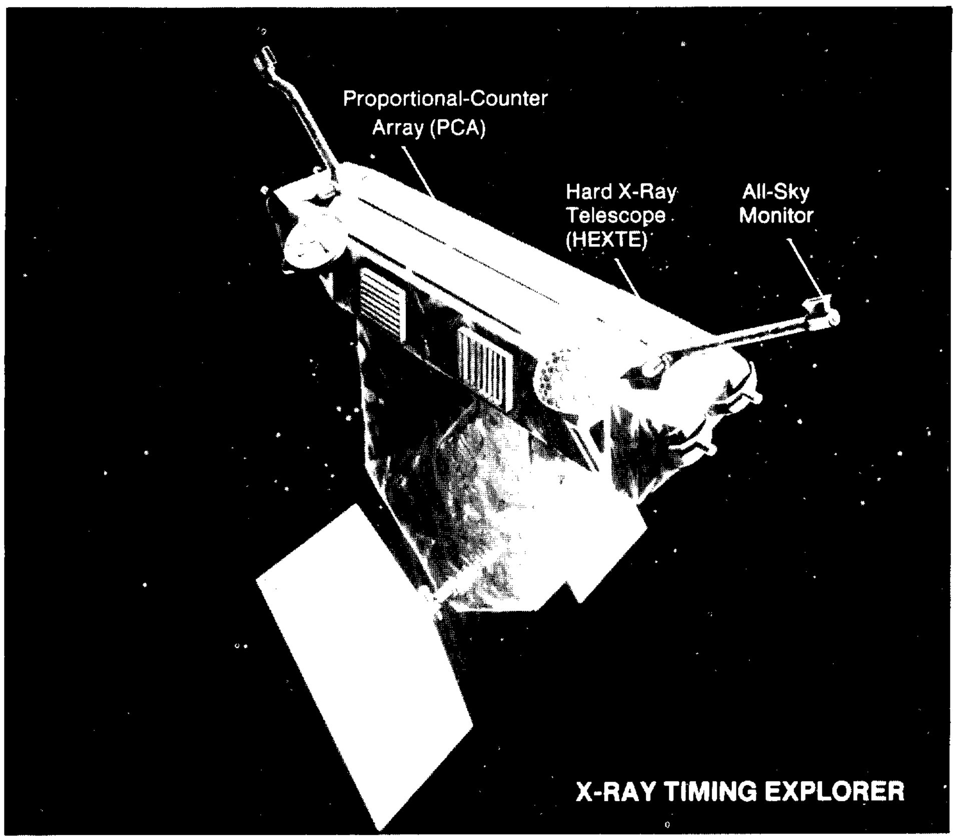

Fig. 2. ***NASA'S X-Ray Timing Explorer,*** or ***XTE. The observational objective of this satellite will be to measure photons from 2 to 200 keV on time scales ranging from 10 microseconds to months. To accomplish this objective, XTE will carry a 1-square-meter proportional counter (PCA), a 0.2-square-meter hard x-ray telescope (HEXTE) consisting of twelve scintillation detectors, and two ail-sky monitors that will scan the sky continuously.*** ➤

very faint sources and of changes in sources on very short time scales that have previously been inaccessible. Sources 10^5 times fainter than Scorpius X-1, for example, will be detectable in 100 seconds, allowing extensive study of active galactic nuclei and faint galactic binaries. Features of bright sources, such as fast variations in intensity, pulse frequency changes, and spectral changes during x-ray bursts. will be resolved without parallel. For example, XTE will be able to collect 2000 photons during a single pulse from the accretion-powered pulsar Hercules X-1, 200,000 photons during a bright x-ray burst. and even 45 photons during a 600-microsecond flare of the fascinating source of Cygnus X-1.

The x-ray transients discovered by EXOSAT, Tenma, and other recent satellites frequently turn out to be key examples for elucidating the physics of such systems. However, they are discovered mostly by luck because there is no all-sky coverage by these satellites. The transients were either detected by another satellite or were detected while the telescope was moving from one known source to another. Both of the new satellites will carry all-sky monitors. ASTRO-C will be able to scan the sky by executing a slow pirouette once each orbit, during the time the source being observed by the LAC is hidden by the earth. The monitor on XTE will continuously scan from two rotating platforms and will detect sources 1000 times fainter than Scorpius X-1 in a single 90-minute orbit. Data from these monitors can be used to redirect the main arrays toward sources showing unusual activity, The monitors will also provide unprecedented information on the day-to-day behavior of hundreds of sources.

ASTRO-C will carry a gamma-ray-burst detector, designed in collaboration with Los Alamos, whose viewing angle is half the sky. What is unusual about this instrument is the juxtaposition of a proportional counter sensitive to x-ray photons and scintillation counters sensitive to gamma-ray photons; such an arrangement means the critical spectra of burst events will be measured to lower energies than before.

ASTRO-C will be a free-flying satellite and will operate, with luck, for at least three to four years. The expectations for XTE are less clear. Its nominal design lifetime is that typical of NASA satellites—two years-but past NASA satellites have often functioned productively tor five or more years. (NASA'S International Ultraviolet Explorer, launched in 1978 with a similar design lifetime, is still pouring out results, and competition by scientists for its use has hardly eased.) Even though the XTE instruments can function almost indefinitely, NASA may choose to operate XTE aboard a recoverable platform and terminate its operation when the two-year design lifetime has elapsed. If so, the initial discoveries of XTE could not be followed up. Especially for the all-sky monitor, two years would provide only a tantalizing glimpse compared to the 10-year Vela 5B mission and the 5-year Ariel-5 studies of very long term changes in the x-ray sky. ■

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An Overview of Compact Sources of X Rays

In all accretion-powered x-ray sources the bulk of the energy for emission is supplied by the fall of matter into the deep gravitational well of a compact object, either a degenerate dwarf, a neutron star, or a black hole. The kinetic energy of the fall is converted to heat and then to x rays either during the fall or when the matter strikes the surface of the star.

X-Ray Stars. Accretion-powered x-ray binaries are distributed through galaxies such as our own (Fig. 1). Almost invariably, such compact x-ray sources are close binary systems in which a compact object with a mass 1/2 to 10 times that of the sun strips matter from a companion star. Frequently, the matter spirals slowly toward the compact object, forming a hot disk (opening figure). The known x-ray stars fall into several different classes.

Accretion-powered pulsars are strongly magnetic rotating neutron stars in close binary systems (Fig. 2). Most are found in massive ($>10\ M_\odot$, where $M_\odot$ is the mass of the sun) systems, although a few have been found in low-mass ($\leq 2\ M_\odot$) systems. When accreting material from the companion star enters the neutron star's magnetosphere, it falls toward the magnetic poles along field lines, causing emission of x rays from the magnetic poles. If these poles do not coincide with the rotation axis, the spinning star will emit two broad beams of x rays that can repeatedly sweep across the earth as the star rotates so that the x rays appear to be pulsed. In addition, the flow of accreting matter to the stellar surface may be partially modulated at the rotation frequency of the star. Typical frequencies are in the mHz to Hz range.

In contrast to accretion-powered pulsars, *rotation-powered pulsars* are powered by conversion of the rotational energy of a strongly magnetic neutron star into electromagnetic radiation. This conversion takes place as the result of the existence of extremely strong electric fields near the star that accelerate charged particles to high energies. These neutron stars lack a companion or one close enough to serve as a source of accreting matter. Some of the youngest and fastest rotation-powered pulsars radiate predominately in x rays. The pulsed emission is thought to be the result of misaligned rotation and magnetic-field axes.

Much of the variation in intensity of binary x-ray sources on time scales of hours to days is due to the orbital motion of the binary, which can produce eclipses and so-called dips—short episodes of partial obscuration. However, in some sources the x-ray intensity is observed to change regularly with a period longer than the orbital cycle. The cause of these *long-term periodic variations* is at present unknown, although a variety of explanations have been proposed.

Galactic-bulge sources are so called because the majority are located in a bulge about the center of our galaxy. Although some may be *black holes*, most are thought to be weakly magnetic rotating neutron stars in relatively old *low-mass binary systems*. Our old friend Sco X-1 is in this category. These systems flicker on a wide variety of time scales but do not produce strong regular pulsations. Those of moderate luminosity exhibit *x-ray bursts* caused by thermonuclear explosions of accreted matter. The bursts, which occur episodically at intervals ranging from minutes to days, last a few seconds and stand out above the flickering emission produced by the continuous rain of matter onto the surface of the star. Some bulge sources exhibit the *quasiperiodic oscillations* that were the subject of such intense discussion at the conference.

Cataclysmic variables are low-mass close binary systems containing a strongly or weakly magnetic degenerate dwarf and are highly variable in both visible light and x rays. They are much more numerous than binary systems containing neutron stars.

Gamma-Ray Bursters. A long-standing puzzle are the sources observed to emit

COMPACT X-RAY SOURCES IN OUR GALAXY

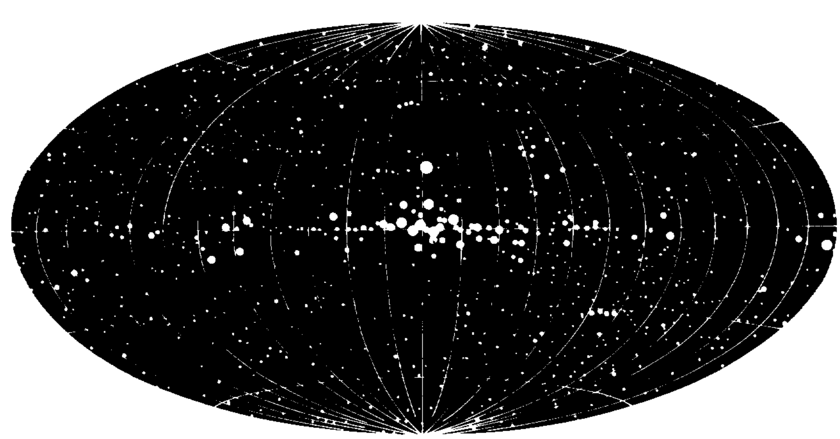

Fig. 1. A recent map of compact x-ray sources in our galaxy prepared using data from the A-1 x-ray experiment on board the HEAO-1 satellite. The radius of the dot representing a source is proportional to the logarithm of its intensity.

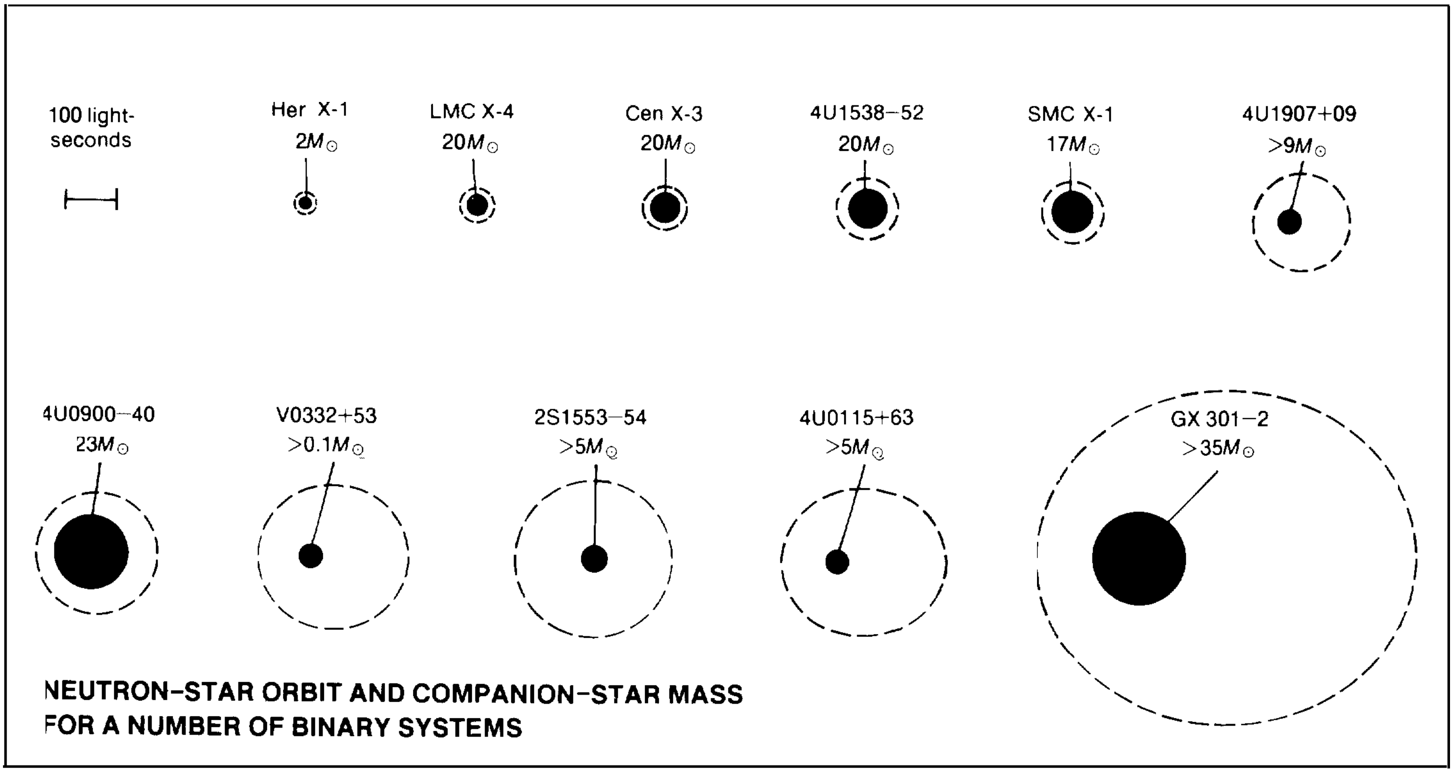

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Fig. 2. The neutron-star orbit and estimated companion-star mass (in terms of the solar mass $M_\odot$) for a number of binary systems. The mass of the neutron star is between ½ and 3 solar masses.

intense bursts of gamma rays lasting a fraction of a second to a few seconds. Accompanying these gamma rays is a relatively weak flux of x rays. Unlike the galactic x-ray stars, which are largely confined to the Milky Way, gamma-ray bursters appear to be randomly distributed over the sky. They are believed to be neutron stars, although the mechanism underlying their bursts remains an enigma.

Active Galactic Nuclei. The nuclei of some galaxies are extremely luminous sources of hard x rays. These sources are believed to be black holes with masses of 0^6 to 10^8 $M_\odot$ that are accreting matter from the surrounding galaxy itself.

All the sources described above vary dramatically on human time scales—a direct result of the fact that the x rays are produced near compact objects. For galactic sources dynamical time scales can be as short as milliseconds, mass-accretion rates as high as 10–8 of a solar mass per year, and luminosities 105 times that of the sun. In active galactic nuclei, dynamical time scales are as short as 102 seconds, accretion rates are believed to be as much as a solar mass per year (a billion times greater than in typical galactic sources), and luminosities are as great as 10^{13} times that of the sun. Because the sources are so compact, these high luminosities come from very small areas (a few square kilometers for pulsars) and the effective temperature of the emitting region is therefore very high. Thus, the photons produced have energies predominantly in the range of 0.01 to 20 kilo-electron-volts (keV) for cataclysmic variables, 2 to 20 keV for pulsars and bulge sources, and 100 keV or more for gamma-ray bursters and active galactic nuclei.

High-Mass X-Ray Binaries

Twenty-three of the twenty-six known accretion-powered pulsars are found in high-mass binary systems (Fig. 2). As discussed above, the stable, periodic pulsations we see from these sources are produced in large part by rotating beams of x rays, Since black holes in such systems would be axisymmetric, stable pulsations are strong evidence that these sources are not black holes. Moreover, the x-ray luminosities of most exceed the maximum luminosity given by radiative-transfer calculations for degenerate-dwarf x-ray sources (about 2 X 10^{36} ergs/second).

Evidence that accretion-powered pulsars are indeed neutron stars comes from observed changes in their pulsation

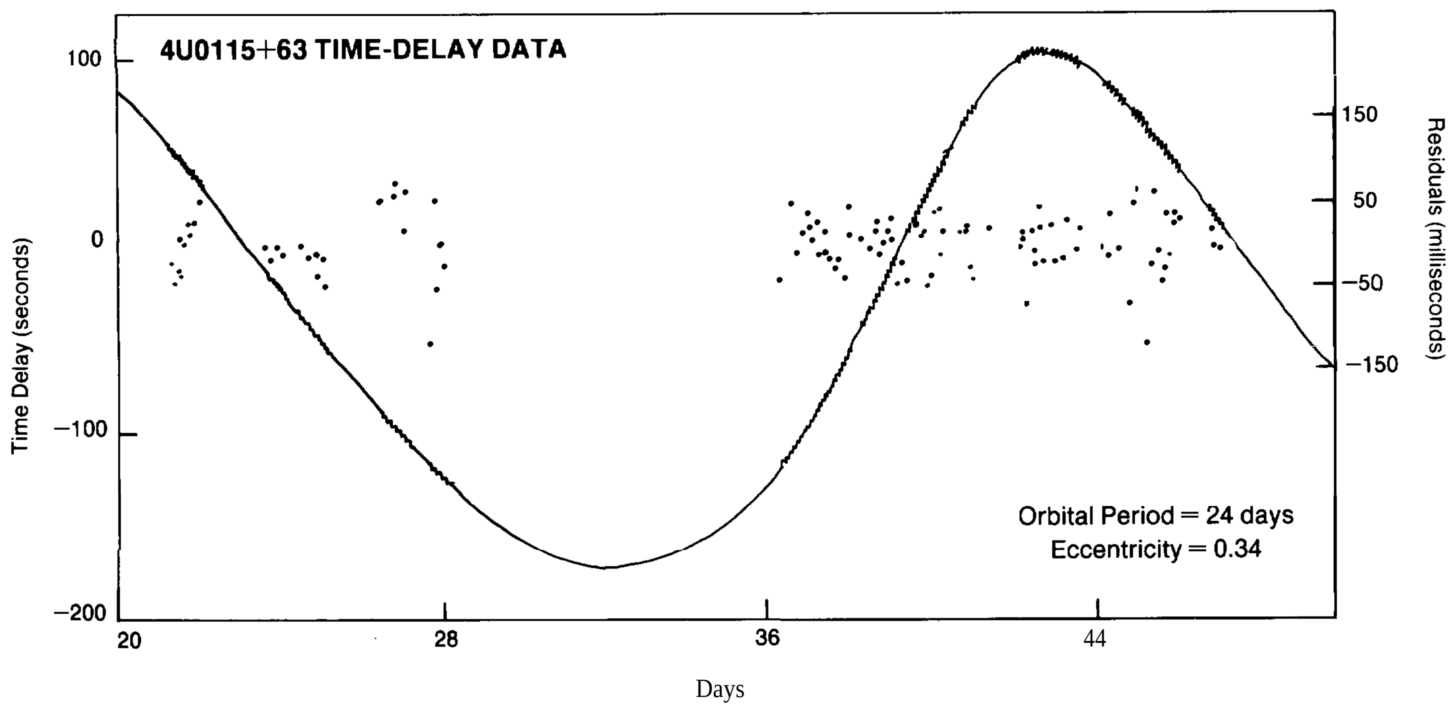

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Fig. 3. The orbital period and eccentricity for the 4U0115+63 binary system are obtained from a fit of time-delay data (black) after the effects of the motion of the satellite around the earth and the motion of the earth around the sun have been removed. The orbital parameters are then used to remove the effects of the motion of the neutron star around its companion, yielding the residuals (red). An analysis of the residuals may uncover variability in the intrinsic spin rate of the neutron star.

Table 1

Orbital parameters for some neutron-star x-ray binaries. The estimated mass of the companion star M_c, which is relatively uncertain, the radius of the companion star R_c, and the allowed range of the mass of the neutron star M are in solar units; the inclination angle i is the angle in degrees between the orbital angular-momentum vector and the line of sight.

System	M_c	R_c	M	i
SMC X-1	17	16	0.8- 1.5	57 to 77
Cen X-3	20	12	0.5- 1.7	>63
4U0900–40	23	31	1.6-2.2	>73
4U1538–52	20	16	1.0-3.2	>60
LMC X-4	20	9	1.0- 1.8	>58
Her X-1	2	4.0	1.1-1.8	>80

frequencies, which agree quantitatively with the changes predicted by the theory of accretion by neutron stars having magnetic fields of 10^{11} to 10^{13} gauss (G). Other evidence comes from the discovery of what appear to be cyclotron scattering lines in the x-ray spectra of two of these systems, indicating magnetic fields in the same range. Such magnetic field strengths are expected for neutron stars. Several accretion-powered pulsars show thermal soft (about 0.5 keV) x-ray emission that is inferred to be coming from a region about 10^3 kilometers (km) in radius, just the radius of the magnetosphere of a neutron star with the appropriate luminosity and with surface magnetic fields of about 10^{12} Finally, the x-ray spectra and pulse waveforms of these pulsars agree qualitatively with those predicted by neutron-star models.

A few high-mass binary systems are thought to contain black holes. These are discussed later (see the section in this article entitled “Black Holes,” page 26).

Pulse Timing. During the past few years, the interplay between theory and observations of pulsars has led to fundamental changes in our understanding of the dynamical properties of neutron stars (see "Internal Dynamics of Neutron Stars") and has uncovered surprising features of the accretion flow patterns in massive x-ray binaries. These advances have been made possible by extremely precise measurements of the intrinsic pulse frequencies of pulsars, carried out with x-ray instruments on satellites such as SAS-3, Ariel-5, HEAO-1, Hakucho, Tenma, and EXOSAT and by the development of new methods of analysis (see "New Analysis Techniques").

Determining the *intrinsic* pulse frequency of the neutron star from the *observed* pulse frequency requires removing the systematic effects of the motion of the observing satellite around the earth, the motion of the earth around the sun, and the motion of the pulsar around its stellar companion. Determining the binary orbit, a major task in itself (Fig. 3), provides valuable information about the mass of the neutron star (Table 1), as well as revealing the structure of the companion star and, over time, the evolution of the binary system.

After the effects of the orbital motion have been removed, the intrinsic pulse frequency can be examined for variations, which are due primarily to changes in the rotation rate of the neutron-star crust. (In principle, changes in the x-ray beaming pattern can also cause variations in the observed pulse frequency. However, where observations have been made that can determine the size of such variations, they appear to be small compared to variations caused by changes in the rotation rate of the crust.) In accretion-powered pulsars, variations approaching 0.01 per cent of the spin rate have been seen to occur within a few days, and changes as large as a few per cent have been observed over the course of a year (Fig. 4).

These variations in the rotation rate of the crust could be caused by *internal* effects, such as changes in the moment of inertia of the crust or in the torque exerted on the crust by other components of the star. Examples of such internal changes include temperature fluctuations, fracture of the star's crust, and unpinning of superfluid neutron vortices in the inner crust (discussed in "Internal Dynamics of Neutron Stars ").

Analysis of relatively small variations in the rotation rates of both accretion-powered and rotation-powered pulsars has led to a new picture of the dynamical properties of neutron stars (also discussed in "Internal Dynamics of Neutron Stars"). In particular, it had been thought that the crust of the neutron star was only weakly coupled to the neutron superfluid that forms most of the core of the star. It is now thought that neutron stars are essentially rigid—that all but 1 per cent of the star is coupled to the crust on time scales longer than a few hundred seconds. According to this new picture, the effect of internal torques on the rotation rates of accretion-powered pulsars can be neglected.

Variations in the rotation rate of the crust can be caused by fluctuating *external* torques, which reflect changes in the star's coupling to its environment. Examples are electromagnetic torque fluctuations, reversals in the flow of accreting material, or fluctuations in the magnetic braking torque that occur when a rapidly rotating star accretes from a disk.

INTRINSIC PULSE-FREQUENCY VARIATIONS

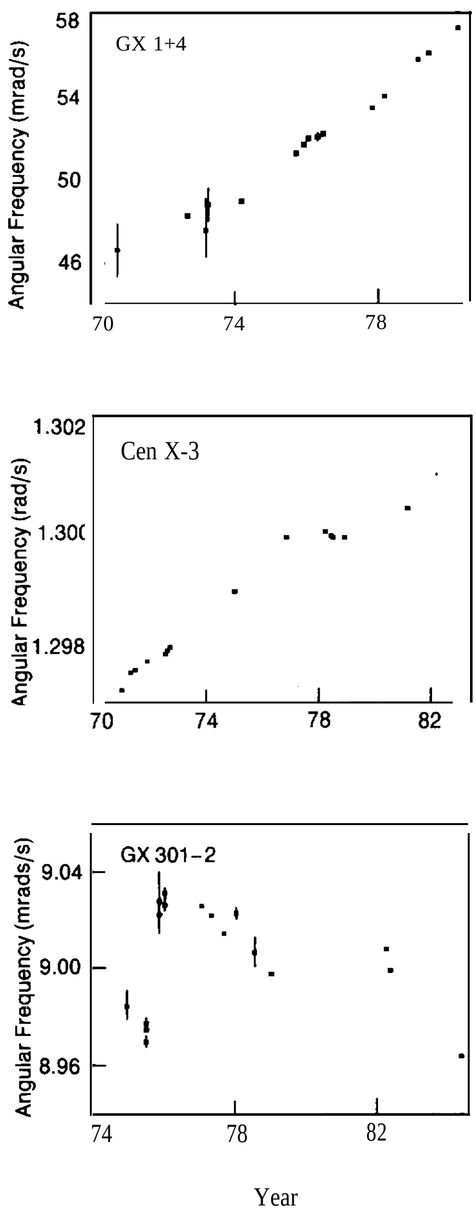
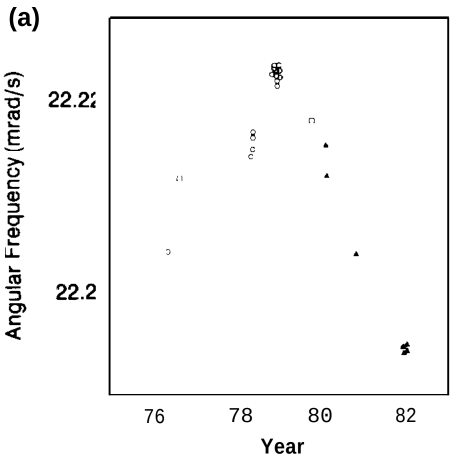


Fig. 4. Pulse-timing results for several accretion-powered pulsars, showing variations in the intrinsic pulse frequency that are most likely due to changes in the rotation rate of the neutron-star crust.

Accretion Torque Variations. If the rotation rate of the crust in accretion-powered pulsars is *not* significantly affected by internal torques as argued above, measurements of the pulse frequency provide direct evidence of the accretion torque on the crust. What do such measurements say about spin-rate fluctuations in accretion-powered pulsars? Analysis of the fluctuations in the spin rate of Vela X-1 over an eight-year period supports the idea that the fluctuations are caused by changing external torques and also reveals interesting properties of the accretion flow.

ANALYSIS OF INTRINSIC PULSE-FREQUENCY VARIATION FOR Vela X-1



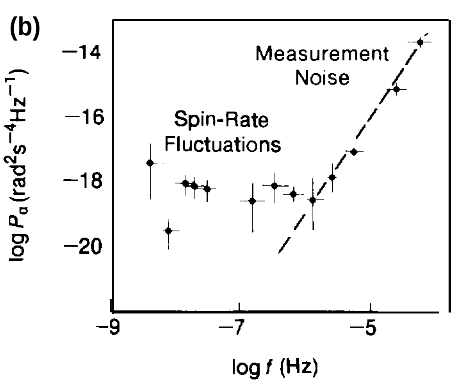


Fig. 5. Pulse-timing results for Vela X-1. (a) Although the change is small (0.5% overall), the pulse frequency, or angular velocity, of the neutron star appears to have increased from 1975 to 1979 and then decreased from 1979 to 1982. (b) The power-density spectrum of fluctuations in the pulse frequency of the star is approximately flat for periods ranging from 5 to 2600 days, which is characteristic of random forces acting on an approximately rigid star. Thus, the long-term rise and fall of the pulse frequency shown in (a) is consistent with torque variations and does not indicate a change in the character of the accretion flow onto the star.

The original pulse-timing data for Vela X-1 (Fig. 5a) appear to show a relatively slow increase in the rotation rate over a four-year period followed by a relatively slow decrease. However, the power-density spectrum of the pulse-frequency variations derived from the same data (Fig. 5b) shows that the long-term rise and fall in pulse frequency is consistent with what would be expected as the result of a fluctuating torque. The spectrum is relatively flat and therefore consistent, for periods ranging from 5 to 2600 days, with white noise in the star's angular acceleration; that is, the behavior is equivalent to a random walk in pulse frequency. The observed noise strength implies an accumulated offset in pulse phase greater than π radians for times longer than 25 days, showing that the observed variations in pulse frequency are due primarily to changes in the rotation rate of the neutron-star crust and not to variations in the radiation beaming pattern.

The rapidity of the changes in the pulse frequency or angular velocity of Vela X-1 is also significant. Average angular accelerations over 3 days are as large as 6×10^{-3} Ω/yr, where Ω is the angular frequency. Moreover, the sign of the acceleration reverses on the 3-day temporal resolution of the observations. These large accelerations and reversals in sign rule out most mechanisms for altering the angular velocity. The simplest conclusion, already suggested by theoretical considerations, is that the random walk in angular velocity is due to fluctuations in the external accretion torque.

If the external torque is indeed responsible for these changes in the rotation rate of the neutron-star crust, then pulse-timing measurements can be used to probe the flow of accreting matter near the star. For example, the sign and magnitude of the accretion torque depend on the accretion rate, the pattern of the exterior flow, and the structure of the star's magnetosphere. Precise observations of changes in the rotation rate can thus provide information about these properties of the flow. In particular, variations in the amount of matter falling on the neutron star should produce *simultaneous* variations in x-ray luminosity and in the angular acceleration of the star's crust. Thus, one of the most direct ways to probe the accretion flow is to plot the observed angular acceleration a as a function of the observed x-ray flux F.

As an example of an expected correlation, consider the case in which matter spilling from the atmosphere of the companion star has sufficient angular momentum to form an extensive accretion disk outside the neutron star's magnetosphere. The torque on the star is then independent of the detailed flow far away but *is* dependent on the radius r_0 separating Keplerian flow in the disk from the flow of matter along field lines of the star's magnetosphere. Suppose that the star is rigid and has a constant moment of inertia. Then, if the flow is steady, the angular acceleration of the star is given by

$$a = n\, M_m (GM\, r_o)^{1/2}/I,$$

where M_m is the mass flow rate into the magnetosphere, M and I are the mass and moment of inertia of the neutron star, G is the gravitational constant, and n is a dimensionless quantity of order unity that depends on the structure of the transition zone between the disk and the magnetosphere. In fact, n may be positive or negative, depending on such parameters as the neutron star's rotation rate and the mass-accretion rate.

What correlation does this equation imply between a and F? Suppose the observable x-ray flux F *is* proportional to M_m. Now, the torque—and hence the angular acceleration—depends on the lever arm r_o, which becomes smaller as M_m increases. Thus, for disk flow, the expected correlation between a and F *is*

$$a \propto F^{6/7} .$$

A second case is wind-fed sources in which matter is captured from a stellar wind with a high enough velocity that it

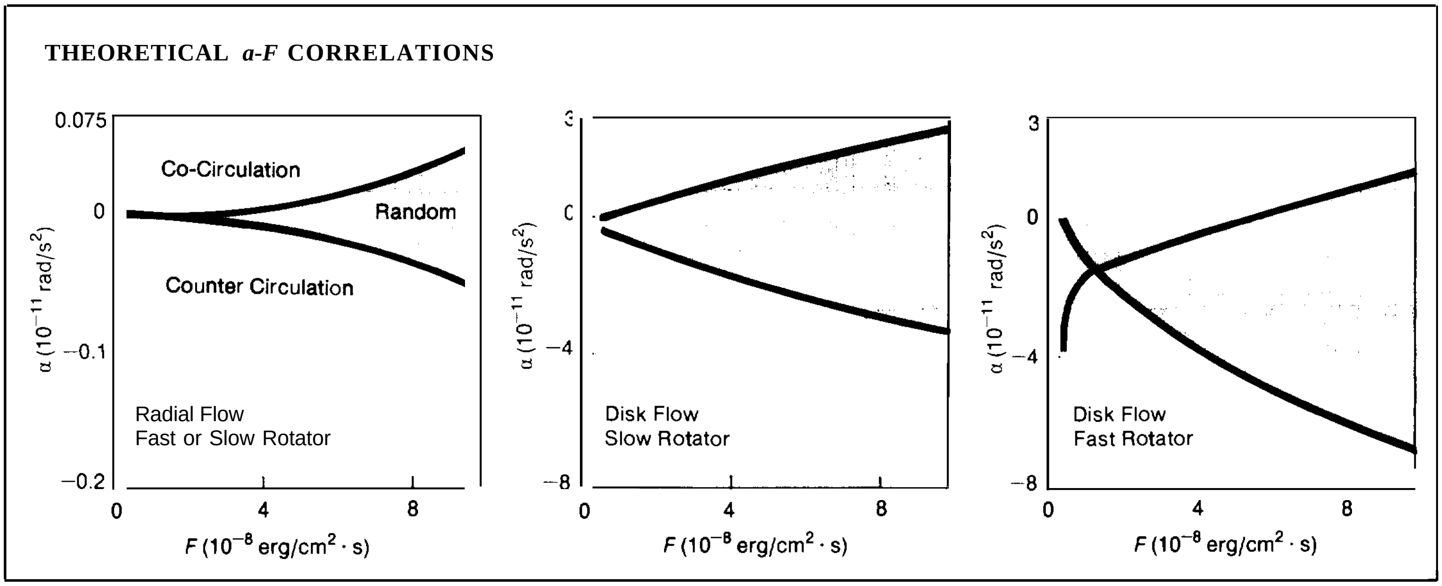


Fig. 6. Theoretical plots of angular acceleration versus x-ray flux (a-F) for various orientations of the angular momentum of the accreting matter. In all panels the red curve represents the case in which the circulation of the accreting matter has the same sense as the rotation of the neutron star, the black curve represents the case in which the circulation is counter to the rotation, and the shaded region represents a random distribution of directions for the angular momentum of the accreting matter. Note that the* a *scale for the left panel (the case of radial flow of accreting matter onto either a rapidly or slowly rotating neutron star) is expanded 40 times that of the other two panels (disk flow). These plots* were *obtained by assuming that the time during which the angular momentum of the flow changes direction is much shorter than the time between changes, so that the flow may be considered stationary most of the time.

does not have enough angular momentum to form an extensive accretion disk. In these sources the radial velocity of the accreting plasma outside the magnetosphere is large, The theory of such radial flows has not advanced sufficiently to predict the precise relation between a and *F*. However, it is known that the sign and magnitude of the torque is quite sensitive to variations in the flow velocity and density across the capture surface. Thus, correlated changes in a and *F* are to be expected.

Flow Reversals. Returning to the pulse-timing data from Vela X-1 (Fig. 5a), the observed reversals in angular acceleration imply reversals in the sign of the accretion torque. There are only two known ways for such torque reversals to arise. For disk flow near a rapidly rotating neutron star, the reversal could be caused by a change in the mass flow rate since this results in a change in the size of the magnetosphere and hence in the relative sizes of the material spin-up torque and the magnetic spin-down torque. For radial flow it could be caused by a reversal in the direction of circulation of the accreting matter. A comparison of the simulated *a-F* correlation for the wind-fed source Vela X-1 (similar to the left panel of Fig. 6) with the correlation derived from data taken with the Hakucho satellite indicates that there is no extensive disk in this system and hence that flow reversals are the cause of the torque reversals.

Such flow reversals are not predicted by the standard model of capture from a wind. Moreover. the measured angular accelerations are some 70 times larger than those predicted by models in which matter is captured from a homogeneous wind. The indicated circulation of the accreting matter is so large that the azimuthal component of the flow velocity at the magnetosphere of the neutron star must be comparable to the Keplerian velocity there (that is, the matter is almost in orbit). But as already pointed out, the sign and magnitude of the torque produced by radial flow is sensitive to spatial variations in the flow velocity and density. Thus, the Vela X-1 observations are consistent with a torque that is produced by capture from an *inhomogenous* wind. Although the x-ray flux variations appear random on time scales longer than 0.25 days, the direction of circulation of the accreting matter appears to persist for much longer times. Evidently, the wind contains coherent structures that are at least as large as the radius of the companion star.

The evidence that the accretion flow in Vela X-1 changes its sense of circulation on time scales as short as 3 days has stimulated theoretical work on accretion flows (Fig. 6). Previous work has assumed that the angular momentum of the accreting matter always has a direction more or less parallel to the orbital angular momentum of the binary system. Obviously, this assumption is wrong. In the case of more general flows, one would like to know both the direction and magnitude of the angular momentum of the flow as a function of time. The spin rate of the accreting star samples only the component of the angular momentum that is parallel to the spin axis. To sample the perpendicular component, it might be possible to observe changes in the spin axis of the neutron star relative to the axis of rotation of the binary system.

Accretion-Flow Puzzles. The results presented at the workshop show that the flow of accreting matter in x-ray binaries is much more complicated than previously imagined. Many basic questions, such as the cause of the relatively small variations in spin rate of rotation-powered pulsars, are not yet settled. The substantial time variability in the Vela X-1 data pose a number of new and challenging problems for theorists. What is the origin of the very high specific angular momentum of the accreting matter? What are the essential features of rings or disks formed by strongly circulating flows that continually change direction? What causes the reversals? Meaningful answers may require multi-dimensional numerical simulations of the kind that are just now becoming possible.

Low-Mass X-Ray Binaries

As discussed above, almost all of the known accretion-powered pulsars are found in high-mass systems. In contrast, the low-mass x-ray binaries, which are mostly found in the galactic bulge, typically do not contain pulsars but exhibit dips, bursts, and quasiperiodic oscillations that reveal new aspects about the physics of the accretion process. In particular, the newly discovered quasiperiodic oscillations in the x-ray flux from low-mass galactic-bulge sources (see "Quasiperiodic Oscillations") promise to be a powerful probe of conditions near the neutron star.

A typical galactic-bulge source consists of a low-mass star spilling matter into the gravitational potential well of a weakly magnetic neutron star. Because the matter captured in the gravitational well of the neutron star has too much angular momentum to fall directly to the stellar surface, it swirls around in nearly circular orbits as the slow transfer of angular momentum outward allows it to inch inward. In contrast to accretion-powered pulsars with their extensive magnetospheres, there may be little or no funneling of material onto the magnetic poles of bulge sources.

The angular momentum transport processes that allow the material to flow inward also heat it. By calculating the energy generated per unit area of the disk as a function of the mass-accretion rate, it can be shown that the inner disk, if it is optically thick, is heated enough to be a strong source of relatively soft (about 1 keV) x rays. However, this heating accounts for only half the kinetic energy acquired by material as it falls into the gravitational potential well of the neutron star. The remainder is lost when the matter interacts with the star, producing very intense emission of harder (about 2 to 7 keV) x rays from the surface.

Inner-Disk Coronae. This simple division into soft x rays from the disk and hard x rays from the neutron-star surface is clouded by the fact that the inner disk may have a diffuse gaseous corona, with radius of order 10^2 km, that can alter the energy spectrum of radiation from the disk or the star or both. The corona may form because of thermal instabilities in the inner disk if the rate of cooling is proportional to the square of the gas density whereas the rate of viscous heating varies linearly with gas density. Thus, regions that are slightly less dense than the density at which heating equals cooling are preferentially heated, which causes expansion, a lower gas density, and an even greater excess of heating over cooling. This process continues until the hot diffuse regions balloon into a corona.

Compton scattering by the hot electrons in the corona can alter the energy distribution of the photons passing through it. If the electron temperature is significantly higher than the energy of the photons, the scattering will, on the average, "blue shift," or increase, the photon energy. When the mean number of scattering for a given electron temperature is not too large, such Comptonization will modify the incident photon spectrum only slightly. As the number of scatterings increases, however, the photons are brought to near thermal equilibrium with the hot electrons. Such "saturated Comptonization" distorts the photon distribution into a so-called Wien peak (at $h\nu \approx 3kT$, where h is Planck's constant, ν is the photon frequency, k is the Boltzmann constant, and T is the electron temperature).

Recent work on the time variability of the x-ray spectra of galactic-bulge sources that takes into account the effects of Comptonization in the corona promises to help unravel the structure of the inner disk and its interaction with the stellar surface. By taking the difference between spectra at different times, a temporally varying hard x-ray component was separated from a constant soft x-ray component (Fig. 7). Although this analysis was done without recourse to a specific model, it is thought that the harder component arises very near the neutron star whereas the softer component arises farther out in the disk. Further interpretation, however, is uncertain, with two alternative models currently able to explain the data.

In model A (left half of Fig. 8) the disk is optically thick far from the neutron star but expands vertically into a low-density optically thin but geometrically thick disk

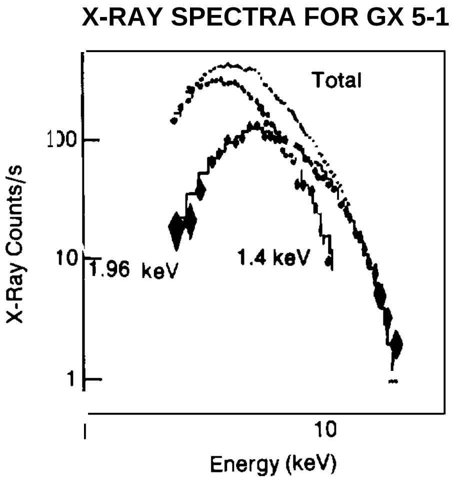
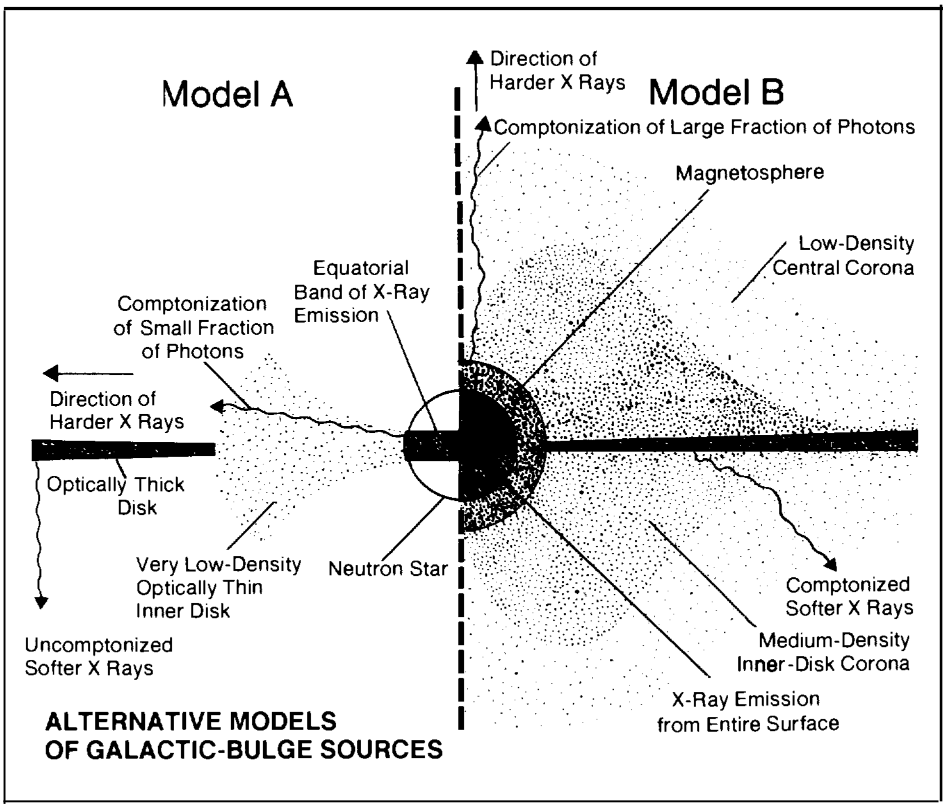


Fig. 7. X-ray spectrum (black) of the galactic-bulge source GX 5-1 decomposed into a softer (red) component (with a 1.4-keV blackbody fit) and a harder (blue) component (with a 1.96-keV fit). The fact that the softer x-ray component is constant in time whereas the harder component is variable allowed the two to be separated by taking the difference of spectra obtained at different times.

near the star. Because the star has no magnetosphere, accreting matter” falls on a belt around the equator. In this model the source would therefore appear brightest in harder x rays if viewed from slightly above or below the plane of the disk. The softer x rays are assumed to come from the optically thick disk without being scattered. A fit to the observed spectrum—assuming the harder component originates from the star and the softer component from the disk—accounts for the entire observed flux except for a high-energy tail. Weak Comptonization of a *small fraction* of the harder x-ray photons that pass through the low-density inner disk explains the tail.

In Model B (right half of Fig. 8) optically thick material extends inward until the disk is broken up by the magnetosphere very near the stellar surface. The star's magnetic field tends to focus the accreting material toward the magnetic poles, but, since the field is too weak to confine it, radiation pressure cause the accreting material to spread throughout the magnetosphere as it falls, heating much of the star's surface. The inner disk has an optically and geometrically thick toroidal corona; in addition, a larger diffuse central corona surrounds the inner disk and neutron star. Thus, softer x rays originating in the optically thick inner-disk material would be scattered as they pass outward through the corona. This type of source would be brightest in harder x rays if viewed along the polar directions where the x rays can leak out without being heavily scattered. Unlike the previous model, a *large fraction* of the hard x-ray photons emitted from the neutron star and its magnetosphere would be Comptonized by their passage through the large central and inner-disk coronae. In addition, the softer x rays from the inner disk would have a spectrum characteristic of unsaturated Comptonization.

Fig. 8. Model A for the bright galactic-bulge sources has an optically thin inner disk and no magnetosphere; material falls onto the star in a narrow equatorial band. If the mass flow rate increases, the inner disk and the band of x-ray emission thicken. In this model the direction of emission of harder x rays is slightly above or below the plane of the disk. Only a small fraction of the photons coming from the star, and none from the optically thick disk, are Comptonized. Model B features optically thick disk material extending inward to a small magnetosphere. A geometrically and optically thick corona of less dense plasma surrounds both star and disk. Radiation pressure spreads accreting material over the star, resulting in emission of harder x rays from the entire surface, but the inner-disk corona makes it harder for them to escape in the equatorial direction. The thick corona Comptonizes a large fraction of the photons emitted from the inner disk and the star.



Although both models are consistent with present data, observations that determine the fraction of Comptonized photons and the best viewing angle for detecting the harder x rays will surely distinguish between them.

Outer-Disk Coronae and Dippers. Strong observational evidence accumulated within the last few years indicates that, besides an *inner-disk corona,* many low-mass x-ray binaries have an extensive *outer-disk corona.* This outer-disk corona is thought to be produced by radiation from the central x-ray source that falls on the accretion disk at a radial distance of 10^4 to 10^5 kilometers and heats it. Such heating evaporates plasma, forming an extensive, hot, optically thick corona above and below the disk. X radiation from the central source is able to heat the disk surface over a substantial annulus because the disk flares, becoming geometrically thicker at greater distances from the x-ray source.

Because of the geometrical and optical thickness of the outer disk and the existence of an extensive outer-disk corona, the character of the observed variation in x-ray flux with orbital phase is very sensitive to the tilt of the binary system, as illustrated by the collection of x-ray flux curves in Fig. 9. Figure 10 shows schematically how such differences are produced naturally by differences in our viewing angle.

If the line of sight is in the orbital plane of the system (Fig. 10, view C), the thick accretion disk will block any direct view of

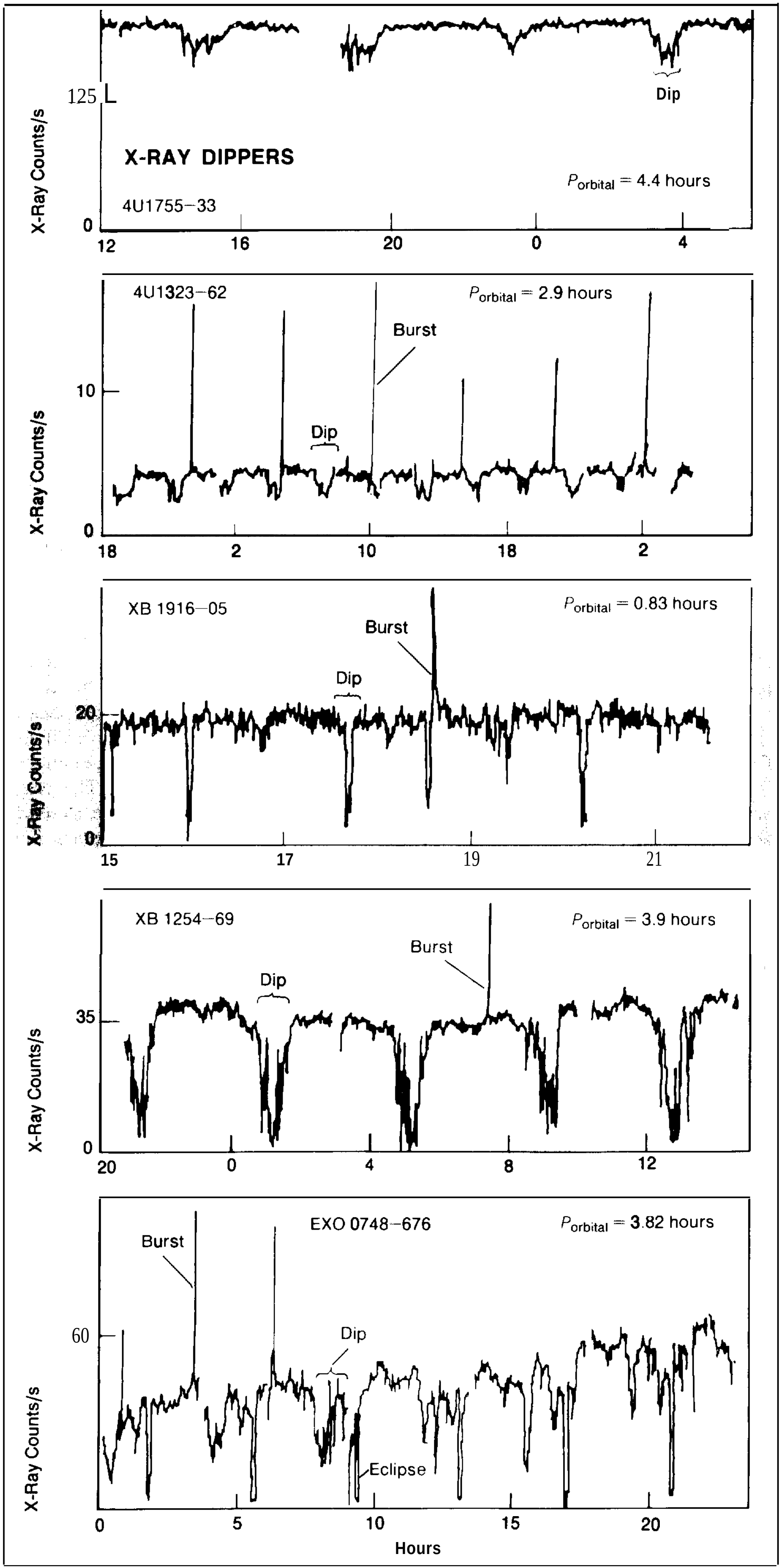
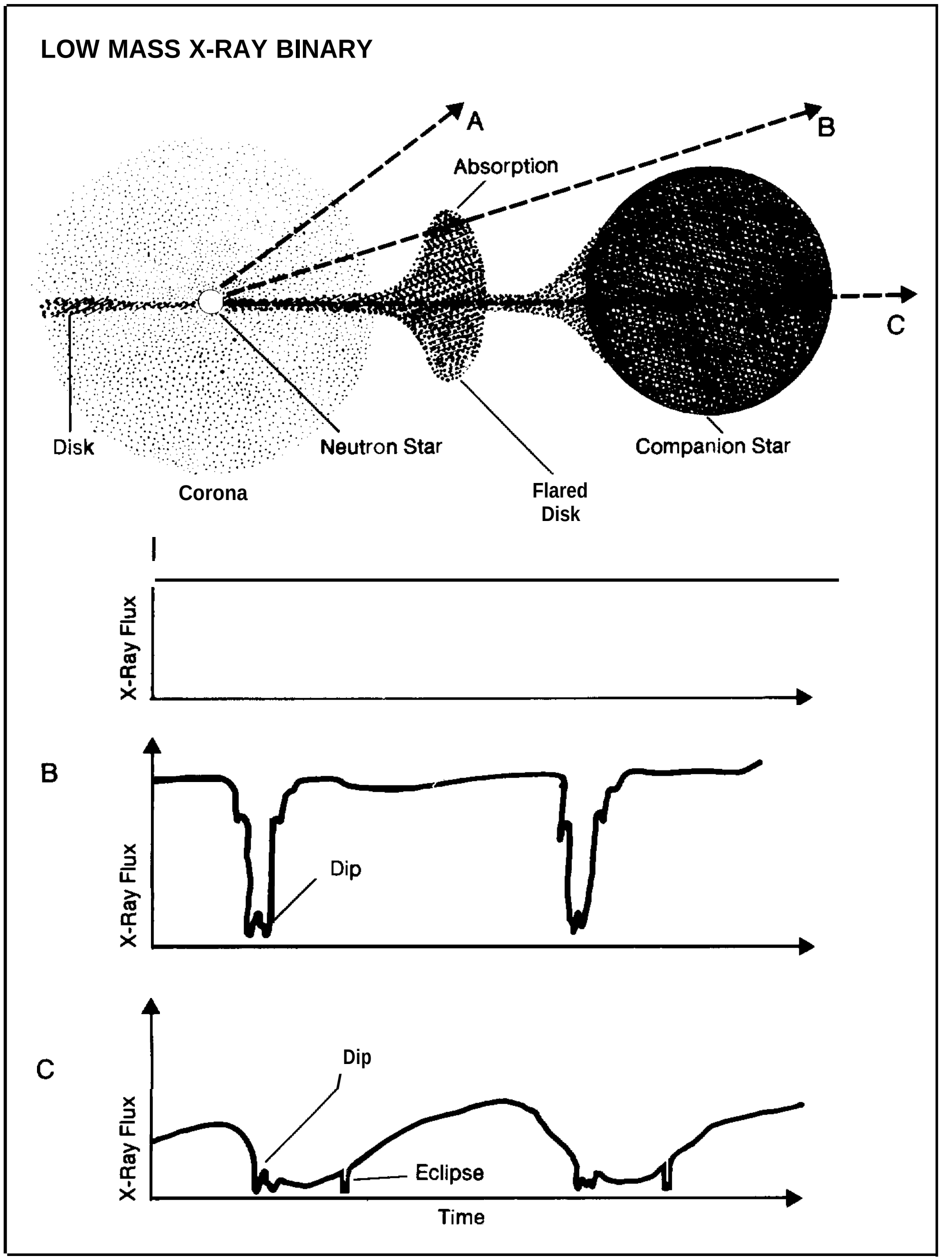


Fig. 9. X-ray light curves for five dippers whose orbital periods range from 0.83 to 4.4 hours. The bottom panel is an example of what is seen when the line of sight is close to the plane of the disk (view C in Fig. 10), whereas the upper panels illustrate what is seen when our sight line is above the disk (view B in Fig. 10). Several of these binaries (see especially 4U1323–62) also exhibit x-ray bursts. ➤

Fig. 10. Low-mass x-ray binaries have such a geometrically thick accretion disk and corona that two different types of periodic variations in the x-ray flux-eclipses and dips-can occur. At high viewing angles (A), the source is seen directly and no flux variations due to orbital motion occur, However, at somewhat lower angles (B), relatively cold gas clumps near the outer rim of the disk periodically swing across the line of sight, generating absorption dips in the flux. For viewing angles close to the disk plane (C), the source cannot be seen directly, and only x rays scattered from the outer-disk corona are observed. As the companion star crosses this line of sight, an eclipse occurs, hut the corona is so large that the scattered x rays are only partially blocked. Absorption dips are also usually evident in this type of light curve. ➤



the x rays from the neutron star. For this reason there are almost no *bright* eclipsing low-mass x-ray binaries. However, some x rays scattered by the outer-disk corona are able to reach us. Even though we are cheated of most of the x rays, the wealth of information they provide compensates for their paucity. When the companion passes across our line of sight we observe an *eclipse,* but because the companion does not cover all the outer-disk corona the eclipse is partial rather than total, that is, the x-ray flux decreases but never reaches zero.

Clumps of relatively cold plasma near the outer edge of the thick disk, such as the splash where the accretion stream from the companion hits, can also block the line of sight. Periodic obscuration by such gaseous structures causes *absorption dips,* and sources exhibiting such dips are called *dippers.* The clumps are literally imaged by x rays just as bodily structures are in medical radiography, the varying transmission of the x rays revealing the complex density structure near the outer rim of the disk.

When our viewing angle of a low-mass binary is just high enough *not* to be blocked by the companion star (view B), we can usually see the central source of x rays directly. Thus, there will be no eclipses, but a highly flared disk may still result in absorption dips. At even higher viewing angles (view A), there is little or no obscuration, and any variation of the x-ray flux must be due to changes in the luminosity of the central source. For example, the regular change in the flux from Sco X-1, probably viewed at an angle of 30 degrees from the normal to the disk, is less than 1 percent.

4U1822–37 (Fig. 11) is a good example of a partially eclipsing source. The smooth variation through the orbital cycle is thought to be due to the varying height of the rim of the accretion disk: as we move around the system, we see more or less of the central coronal cloud over the rim. The secondary minimum is thought to be due to obscuration by a vertically thicker region produced where the accretion stream from the companion star collides with **the disk.**

Several of the dippers shown in Fig. 9 exhibit sudden bursts of x rays, supporting the idea that x-ray bursters (discussed next) are close, low-mass binaries. The exceptional transient EXO 0748–676 is an example of such a system. Not only is it an x-ray burster, but it also exhibits both absorption dips and a total x-ray eclipse with a 3.82-hour period, confirming that the period of the absorption dips is indeed the orbital period. The relative phase between the dips and eclipses puts the fat region of accretion splash just where it would be expected on the disk for an accretion stream that curves between the two moving components of the binary. The same phase relationship holds for dippers in which optical measurements give the phase of the system: the dips occur just before the companion star occults the neutron star.

X-Ray Bursts. Until now we have focused on x-ray variability that has been fairly gentle, that is, changes in the x-ray flux by, at most, factors of order unity, caused by variable accretion rates, orbital motion, or geometric effects. Low-mass binary systems also show sudden, extreme bursts in x-ray flux.

One type of x-ray burst, called Type I, has been explained with great success as a thermonuclear flash on the surface of the neutron star. The details of such bursts, however, still present some enigmas whose solutions may tell us much about these binary systems and the structure of their neutron stars.

Only one star has been observed to exhibit Type II bursts, which are thought to be the result of some type of accretion instability. Although the nature of the instability is unknown, the great regularity of the Type II bursts suggests that some fundamental property of low-mass binaries has yet to be grasped.

Figure 12 shows the hundred-fold increase in x-ray flux and the three-fold increase in emission temperature typical of a

4U1822–37: A PARTIALLY ECLIPSING SOURCE

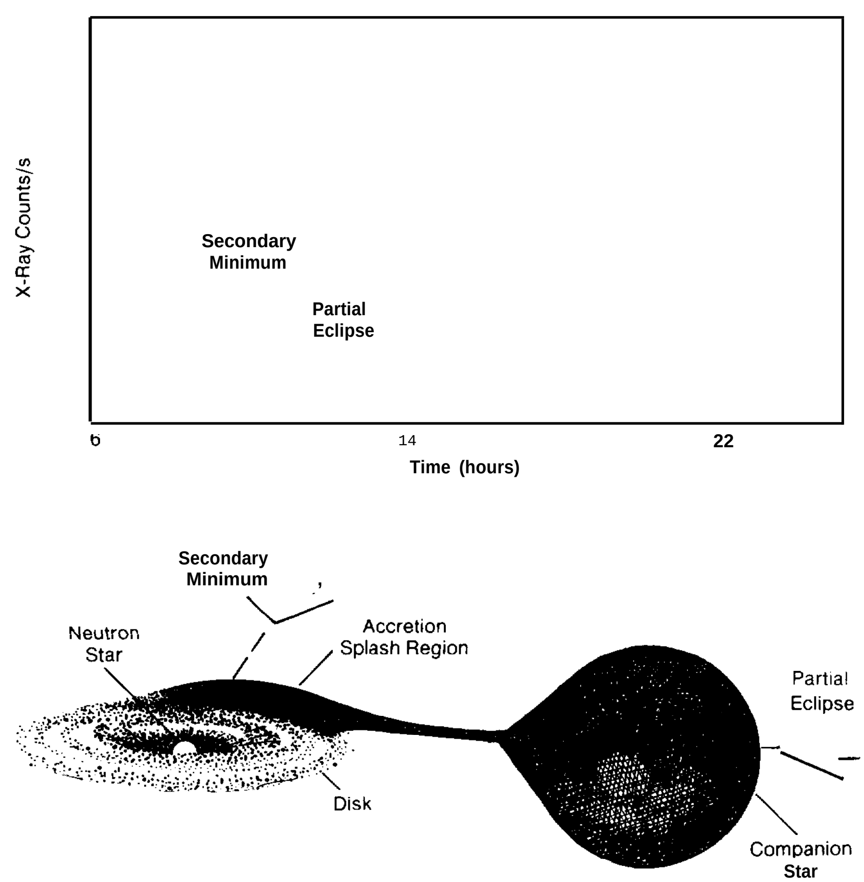
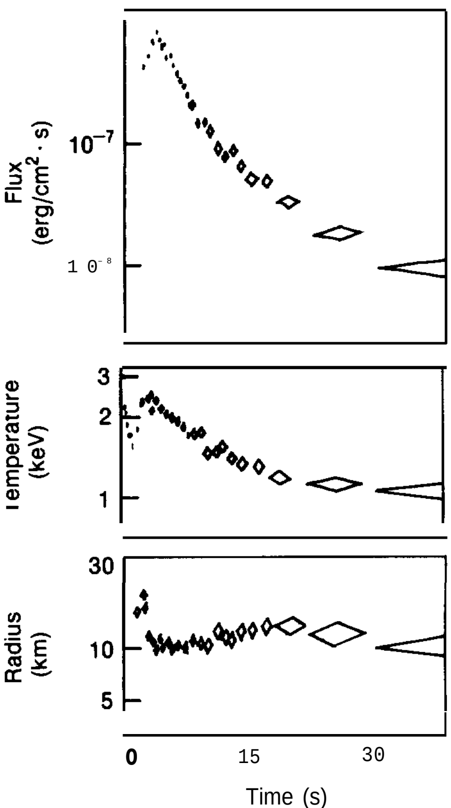


Fig. 11. X-ray light curve for 4U1822–37, a low-mass binary. The secondary minima in the data are most likely due to obscuration of the line of sight to the x-ray source by a thick region where the stream of accreting material hits the disk; the partial eclipse is caused by blockage of the line of sight by the companion star. The fact that the flux does not diminish to zero during the eclipse means that the x rays come from a region larger than the companion star. Since we know of no way to generate the x-ray energy in such a large region, we infer that we are seeing x rays scattered by a large outer-disk corona. As the binary rotates, more or less of this flux is blocked by the structure of the outer disk or the companion. ◀

X-RAY BURST DATA FOR 4U1636–53



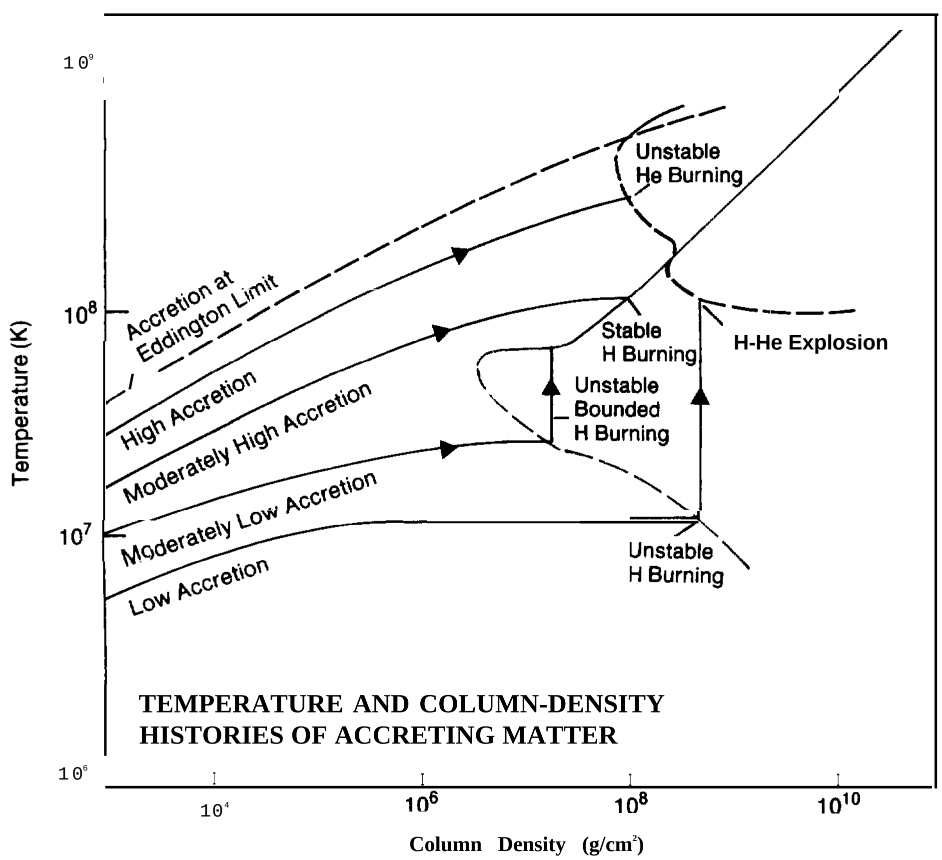
▲ ***Fig. 12, X-ray burst data for 4U1636–53, showing the hundred-fold variation in flux typical of such bursts (top) and the spectral temperature of the emission (middle), These two sets of data can be used to calculate the radius of the photosphere of the source (bottom), which, except for the initial rise and fall, remains of the order of 10 km, implying that roughly the entire surface of the neutron star is emitting,***

Type I burst. During most of the burst, the size of the radiating area, deduced from the flux and temperature, is of the order of 10 kilometers, consistent with emission from the entire surface of the neutron star.

The accepted mechanism for Type I bursts is that newly accreted gas, rich in hydrogen and helium, ignites under conditions of high pressure and density and explodes. Although the details of the process are intricate and are still being worked out, we can illustrate the relevant physics by assuming steady-state accretion and a particular stellar luminosity, which, in turn, fixes the internal temperature gradients (averaged over many bursts).

As a given element of accreted matter is buried deeper in the star by subsequent accretion, its temperature rises according to a predictable curve until eventually the temperature becomes high enough that the matter ignites (Fig. 13). Depending upon

Fig. 13. The temperature and column-density histories (black) of elements of accreting matter being buried deeper and deeper on the surface of a neutron star (with a mass of 1.4 $M_\odot$ and a radius of 6.6 km). The hydrogen ignition curve is shown in blue; the helium ignition curve is shown in red. If the slope of either of these curves is positive (solid lines), burning is stable, This happens because the temperature and column-density changes caused by the burning keep the element of matter from departing significantly from the ignition curve. If the slope of the ignition curve is negative (dashed lines), the opposite happens, and burning is unstable. Low accretion rates result in unstable hydrogen burning followed by a rise in temperature and a hydrogen-helium explosion. Moderate accretion rates result in either stable hydrogen burning or unstable but bounded hydrogen burning. High accretion rates cause the helium to ignite first, resulting in unstable burning and a hydrogen-helium explosion. Also shown (dashed black) is the temperature and column-density history of an element of matter accreted at the maximum rate permitted by the Eddington limit. ▼



the accretion rate, four outcomes are possible. At the lowest rates, the hydrogen ignites, the burning is unstable, and the temperature rises until a combined hydrogen-helium explosion occurs. At moderately low rates, the hydrogen burning is unstable but bounded, and only small flashes are generated that are imperceptible to distant observers. At moderately high rates, the hydrogen burning is stable. In the latter two cases, a helium explosion occurs after the hydrogen is consumed and the temperature has risen enough to ignite the heavier element. At high accretion rates, the helium ignites first, and the burning is unbounded, resulting, again, in a combined hydrogen-helium explosion.

The maximum accretion rate is limited by the fact that the rate of energy release by accretion cannot exceed the *Eddington luminosity.* At the Eddington luminosity the outward force on the accreting electrons due to radiation pressure just equals the inward gravitational force on the ions. Above this critical luminosity, matter falling inward that would have been accreted is instead expelled. The radiation pushes mainly on the electrons, whereas gravity acts more strongly on the ions. Thus, the Eddington luminosity depends on the composition, in terms of the number of electrons per unit mass, of the star's atmosphere: a composition of helium and heavier elements has a luminosity limit about 1.75 times that for a solar atmosphere composition (75 per cent hydrogen).

These steady-state models introduce many of the ideas thought to be relevant to Type I bursts but are not, in fact, in good agreement with all the data. These models explain well the rise and decay times of individual bursts but do not give the proper ratio of time-averaged burst energy to total energy. (Only a few per cent of the average luminosity can be due to nuclear burning; most is due to the release of the gravitational energy of the accreted material.) Relaxing the steady-state assumption may resolve this problem. Moreover, a non-steady state is more consistent with evolutionary ideas since the time needed for the neutron star to come to thermal steady state is many thousands of years, whereas there is good evidence that the mass-accretion rate varies much more rapidly.

For Type I x-ray bursts, the Eddington limit not only sets an upper bound on the mass-accretion rate but also constrains the maximum x-ray flux during a burst. When the luminosity of a star whose atmosphere is initially static rises slightly above the Eddington limit, the outer layers are expelled and luminous energy is converted to kinetic energy of the matter being flung outward. Further increases in total luminosity impart more energy to the ejecta but do not increase the amount of escaping electromagnetic radiation.

The peak luminosities of Type I x-ray bursts show evidence of reaching Eddington luminosity saturation and can therefore be used to infer the surface composition of the neutron stars and the intrinsic luminosities of the bursts. Consider a neutron star with an atmosphere consisting of a hydrogen-rich layer on top of a helium-rich layer (the product of earlier hydrogen burning). When the luminosity reaches the Eddington limit for the *hydrogen* layer, that layer is expelled, pushing the photosphere to a larger radius (Fig. 14). After most of the hydrogen is expelled, the electromagnetic luminosity can rise further to the Eddington limit for *helium.* If the total rate of energy output rises beyond this limit, the excess power will cause the helium atmosphere to expand. As the burst wanes, the star radiates at this upper limit while the radius decreases to its original value. Finally, the luminosity falls below the helium Eddington limit, and the atmosphere returns to its hydrostatic configuration. This explanation is strongly supported by the fact that peak-flux-distribution data show the gap predicted by the 1.75 factor that distinguishes the Eddington limit for a hydrogen-rich atmosphere from that for a helium-rich atmosphere.

By assuming that the peak luminosities

TIME SEQUENCE OF X-RAY BURST FOR 4U1636−53

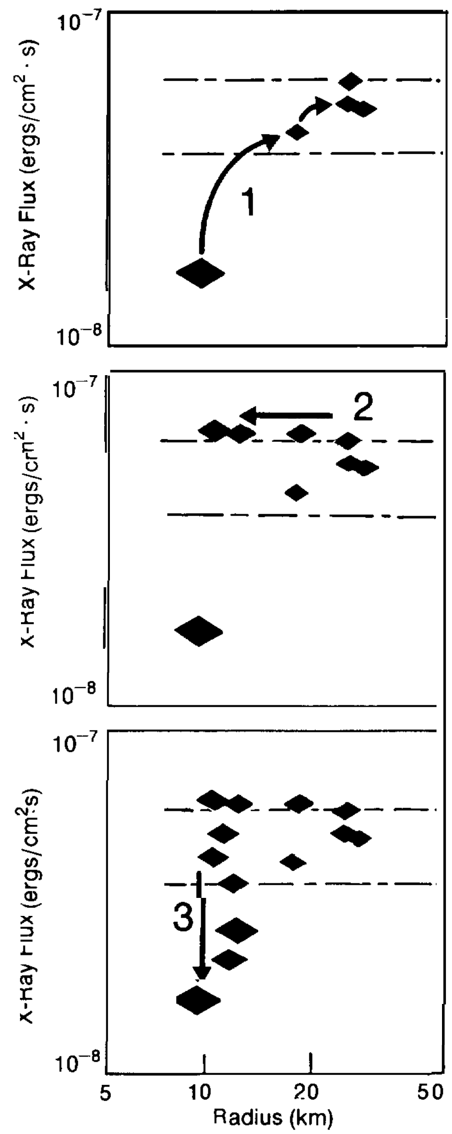


Fig. 14. During an x-ray-burst of 4U1636−53 the photosphere (and, hence, presumably the atmosphere) of the star expands (red) in two stages: once as the burst power reaches the limit for the outer hydrogen-rich layer, and again as the power reaches the higher limit for the helium-rich layer. Eventually, the radius of the photosphere decreases, but the release of gravitational energy as the atmosphere subsides keeps the star radiating at the Eddington luminosity for helium (dark red). As the burst decays, the total luminosity falls (black).

of Type I bursts are accurately determined by the Eddington limits, the observed x-ray flux density has been used to calculate the distance to these sources. Since x-ray bursters, like other galactic-bulge sources, should be distributed symmetrically about the galactic center, their mean distance, so calculated, provides a new, independent measure of the scale of our galaxy. This analysis gives the distance to the galactic center as 6 to 7 kiloparsecs, as opposed to the 8 to 9 kiloparsecs derived by older methods. Since the scale of our galaxy has been used as the standard ruler for all extragalactic scales, cosmological distances may have been overestimated by 30 per cent. Further studies are required to prove that the peak luminosities are generally Eddington, as shown in individual cases by data like those in Fig. 14, and that the bursters we see are not biased to our side of the galaxy.

Type H x-ray bursts, which occur in one x-ray burster that also emits Type I bursts, have a time-averaged power that is too large by at least a factor of 25 to be caused by thermonuclear explosions. The time-averaged power in the Type II bursts is comparable to the total luminosity of the source. This fact means the bursts must draw on nearly all the gravitational energy released by the accreting matter (about 10 per cent of the rest-mass energy of the accreted material). These bursts are clearly caused by an accretion instability.

Figure 15 shows the recently discovered regularities in the decay curve of Type II bursts. These regularities may provide the key to the nature of the instability. When each burst is scaled according to the characteristic time for structure in its decay, all bursts are seen to go through the same cycle of rises and falls. Moreover, the characteristic time appears to increase with total energy output. This type of behavior is reminiscent of a simple mechanical arrangement of springs with a spring constant that changes from event to event; however, we do not know what corresponds to the springs in the burster and what tightens and loosens them.

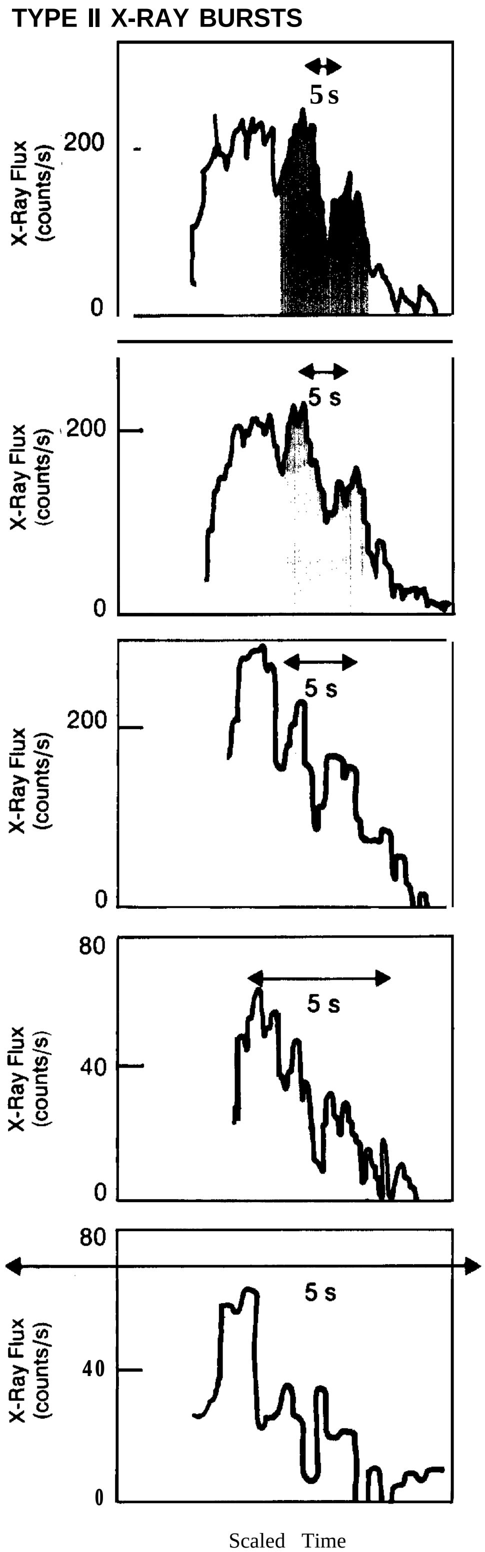


Fig. 15. Observed x-ray intensity curves for Type II bursts. Each of these curves has been normalized to the characteristic time for the rising and falling structure in the decay (note the 5-second indicator in each curve), showing the similarity of the oscillations during the decay. Such time histories are reminiscent of a mechanical arrangement of springs with spring constants that change with total energy output. The event depicted by the top curve has the highest total energy output and the longest oscillation period; the event depicted by the bottom curve has the lowest total energy output and the shortest period. ◄

Long-Term Periodic Variability

X-ray flux variations due to the orbital motion of the two stars in an x-ray binary, such as eclipses, dips, and smooth variations at the orbital period, are expected. Occasionally, however, variations are observed that have a period longer than the basic orbital cycle.

The moderate-mass system Her X-1, with its 35-day variation, is the most famous example. Some massive x-ray binaries with bright, young companion stars have similar cycles. In the Large Magellanic Cloud LMC X-4 shows a 30.5-day cycle that varies in period by no more than 3 per cent per cycle (top panel of Fig. 16). The supergiant systems SMC X-1 (in the Small Magellanic Cloud) and Centaurus X-3 have very sloppy 60- and 130-day cycles—the variation in the period is 15 to 20 per cent per cycle. A long-term periodic variation is also seen in the probable black hole system Cygnus X-1, whose flux changes by 25 per cent every 294 days.

These intriguing periodicities might be due to precession of the accretion disk or of the spinning neutron star, variations in the shape of the accretion disk, the presence of a third star in the system, periodic changes in the wind flowing from the companion star, or some combination of these

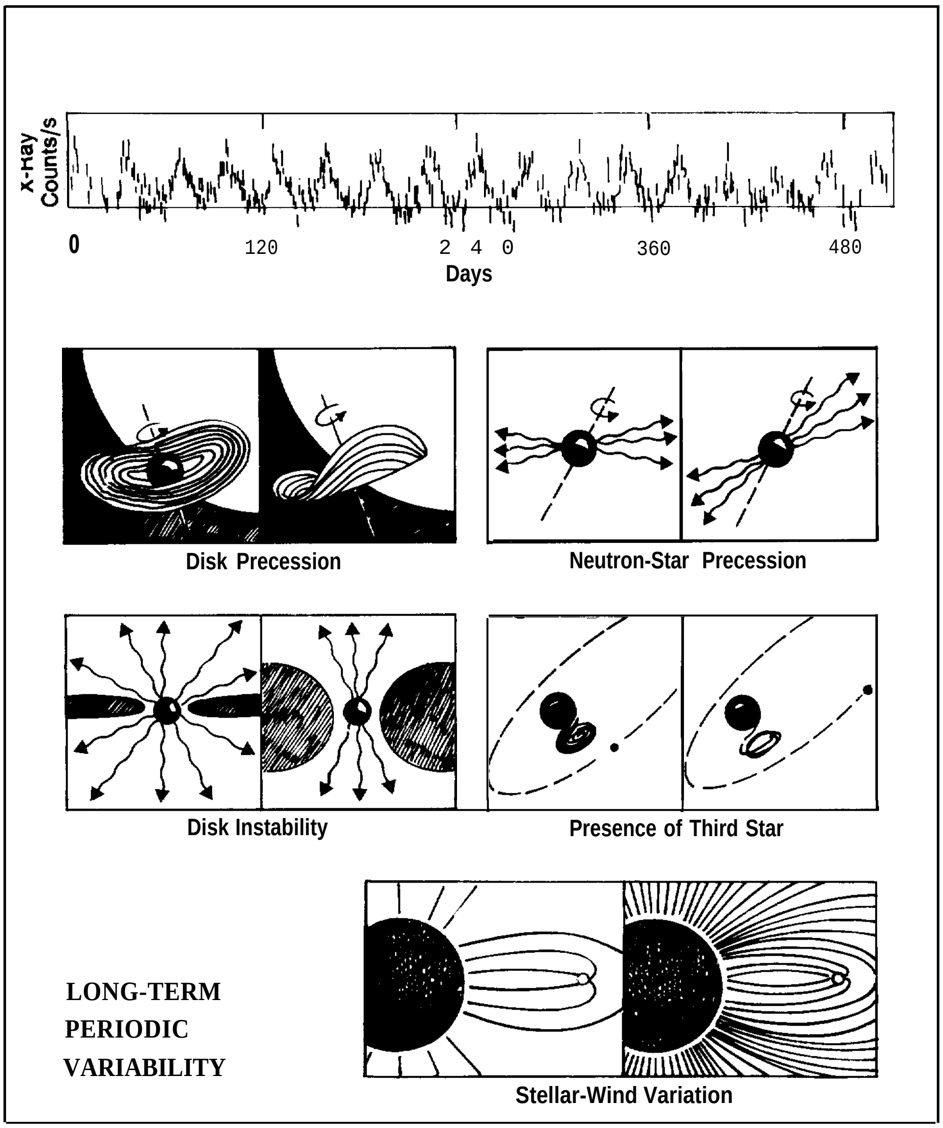


Fig. 16. The observed periodic long-term variation of the flux of LMC X-4 (top) and possible causes of such variation in this and other x-ray binaries. These causes include precession of a tilted disk, precession of the neutron star itself, a disk instability that periodically blocks part of the x rays, modulation of the flow of accreting matter by the tug of an orbiting third star, and variation in the stellar wind of the companion. ◄

(Fig. 16). Study of these variations may provide crucial evidence concerning the nature of the binary system. For example, conclusive evidence that the compact object is processing would rule out the possibility that it is a black hole because such an object would be axisymmetric.

Some neutron stars may have an accretion disk with a twisted, tilted pattern that rotates slowly, periodically blocking the x-ray flux received at earth. One popular explanation for a tilted disk is that the outer layers of the companion star itself are tilted so that the tug of the neutron star causes these layers to precess, altering the direction from which material flows into the disk. On the other hand, the mass transfer may itself be asymmetric, causing the disk to tip and thus to precess.

Neutron-star precession causes the cones swept out by the rotating x-ray beams to cycle up and down with respect to the spin axis of the star, which is almost fixed in space. Recent evidence from Her X-1 (see "Her X-1: Another Window on Neutron-Star Stucture") suggests that the neutron star in this system is processing with a 35-day period, changing the illumination of the companion star. This changing illumination is thought to produce asymmetric mass flow from the companion to the outer rim of the disk, causing the outer rim to be tilted. Precession of this tilted outer rim then causes it to periodically obscure the neutron star, giving rise to the observed 35-day variation in x-ray intensity.

The stars in our galaxy are not only single or double systems; they often are in close systems of three or more. The regularly changing gravitational tug of a third star moving in a distant eccentric orbit about a close x-ray binary could modulate the flow of matter between the inner two stars, producing long-term variability in the x-ray flux. However, no direct evidence has yet been found for the presence of a third star in the systems known to exhibit long-term periodicity.

The outward flow of material from solitary stars with stellar winds clearly waxes and wanes, with one possible cause being a solar-type magnetic cycle. In a binary system, such a cycle on the companion star might regularly modulate the mass flow. A change in the mass-flow rate directly changes the x-ray brightness by changing the rate at which gravitational energy is released as matter falls toward the neutron star. Perversely, though, too much flow toward the x-ray source might actually cloak it, increasing x-ray absorption and causing a net decrease in the x-ray flux seen at the earth.

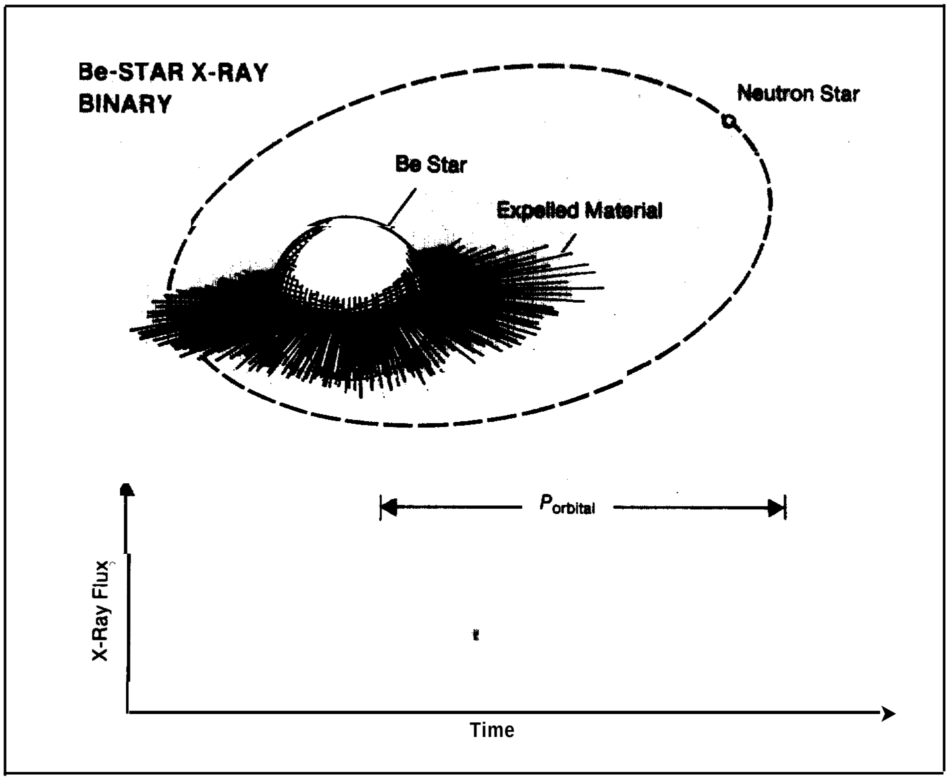


***Fig.** 17. An x-ray binary system consisting of a young, hot Be star and a neutron star in eccentric orbit may show periodic x-ray flares that occur once an orbit when the neutron star is closest to the Be star and its equatorial wind or disk of expelled material.* ◀

Instabilities in the accretion disk that might cause it to fatten periodically and obscure the x rays emitted from the neutron star could also result in long-term variability. A persistent fat disk may have obscured Her X-1 during a period in 1983 and 1984, causing its apparent disappearance in x rays (we know the x-ray source remained on because it continued to heat the near face of its companion, as usual).

Some sources vary over a long time period simply because they take a long time to travel around a wide orbit. A good example is some Be stars with a neutron-star companion in an eccentric orbit (Fig. 17). A Be star is a hot young star that is spinning so rapidly that it expels matter, creating a massive wind, a disk of ejected material around the rotation equator, or both. The x-ray signature of this type of binary system is periodic outbursts that occupy only a small part of the cycle—presumably that part when the neutron star is closest to its companion and is moving through dense, low-velocity material that it can accrete voraciously. The period of the outbursts, which has been observed to range from less than 10 days in some systems to almost 200 days in others, should thus be the same as the orbital period. This is the case for many systems, especially those with long periods, but not for some, such as 4U0115+63, which has an outburst period of about 30 days. In systems in which the period of the outbursts differs from the orbital period, cyclical activity of the Be star may be the dominant effect.

If interaction of a neutron star with an equatorial disk around the Be star is the cause of outbursts, then the neutron star is a splendid probe of the Be star's mass loss. However, before we can exploit this tool in any particular system, we need to confirm that we are indeed seeing the *orbital* period and not an activity cycle on the Be star that, because of some underlying clock, periodically expels matter. This may best be done with precise timing measurements as the pulsing neutron star moves around its orbit; however, changes in the spin rate of the neutron star driven by the varying accretion rate confuse such analyses. We also need to understand why the shapes and commencement times of certain gigantic outbursts are not controlled simply by the orbital motion. Do some events, for example, the 1973 eruption of V0332+53 and the 1975 and 1980 eruptions of A0535+26, simply choke at a maximum flow rate? Or is there a minimum acceptable accretion rate such that, near the threshold, a small variation in mass supply switches the source on and off, whereas, at higher accretion rates, the luminosity vanes smoothly? Most important, we need to know the physics of the flow of matter from the Be-star disk to the neutron star. It is not yet clear whether a disk forms around the neutron star, whether matter from the Be star accretes directly into the neutron star's magnetosphere, or whether, as is likely, both occur.

We should also include in long-term variations certain semi-regular cycles, with periods of 0.5 to 2 years, detected in several low-mass x-ray sources, such as the bursters 4U1820-30 and 4U1915–05. These are probably caused by changes in the rate of mass flow from the companion to the neutron star, with the enhanced rate of mass transfer lasting for 50 to 100 days. The reasons for the enhancement are not well understood, though analogous behavior has been seen in close binaries that contain degenerate dwarfs rather than neutron stars.

Gamma-Ray Bursters

A bewildering category of violent events that is even more spectacular than the x-ray burst is the gamma-ray burst. The sources of these events have never been clearly observed during their quiescent periods because they are extremely faint in all parts of the electromagnetic spectrum. However, during an outburst, which typically lasts a few seconds, each of these sources is by far the brightest gamma-ray source in the sky, outshining everything else combined, including the sun.

Despite the dramatic nature of gamma-ray bursts, little has been deduced about the characteristics of their sources. Two features in the observed radiation give us clues: one appears to be emission from positron-electron annihilation that has been gravitationally redshifted; the second appears to be cyclotron lines from plasma in magnetic fields of the order of 1012 G. Either of these interpretations, if correct, is a strong indication that the sites for the bursts are neutron stars and not, say, black holes. Beyond this one point, however, there is no general agreement about the nature of the bursts. Current proposals include asteroids falling onto the neutron star, thermonuclear explosions, and sudden adjustments in the angular-momentum distribution of the neutron star.

Recent simultaneous x-ray and gamma-ray observations of gamma-ray bursts have shown the bursts to be extremely clean sources of gamma rays. Even though other objects produce copious fluxes of gamma rays, no other object produces such a high ratio of gamma rays to x rays (Fig. 18). Evidently the radiation from gamma-ray bursters is extremely non-thermal and does not degrade into many lower-energy photons. This constraint raises strong doubts about many previous assumptions about the nature of gamma-ray burst sources.

For example, it has been assumed that the gamma rays are produced by electrons losing most of their energy as synchrotrons radiation, a process that takes only about 10^{-15} of a second in a 10^{12}-G magnetic field. However, the spectrum from this process would have too much x radiation by at least a factor of 10. Likewise, if, as is generally assumed, the gamma rays are emitted in all directions from a region near the stellar surface, the surface would heat up and radiate too many x rays. Such considerations suggest that the gamma radiation in a burst may be collimated away from the stellar surface. Gamma-ray bursters remain one of the great unsolved mysteries of our time.

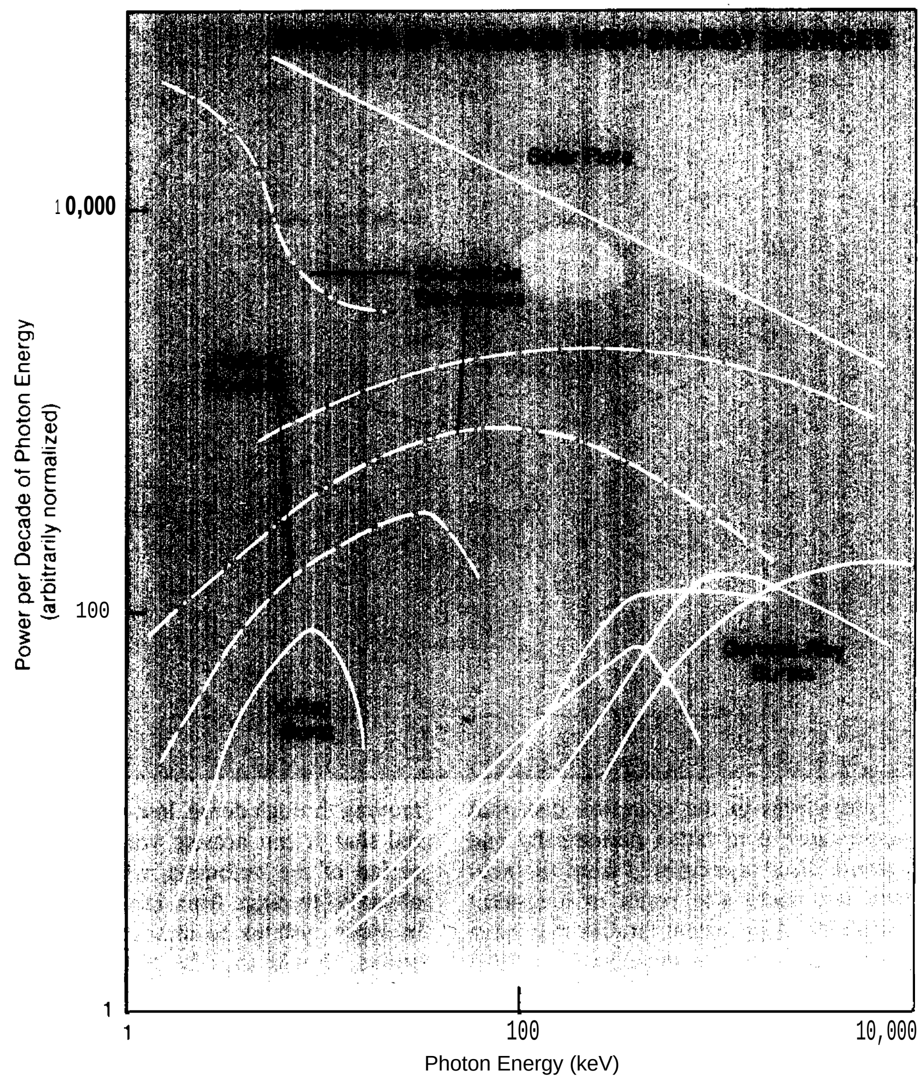
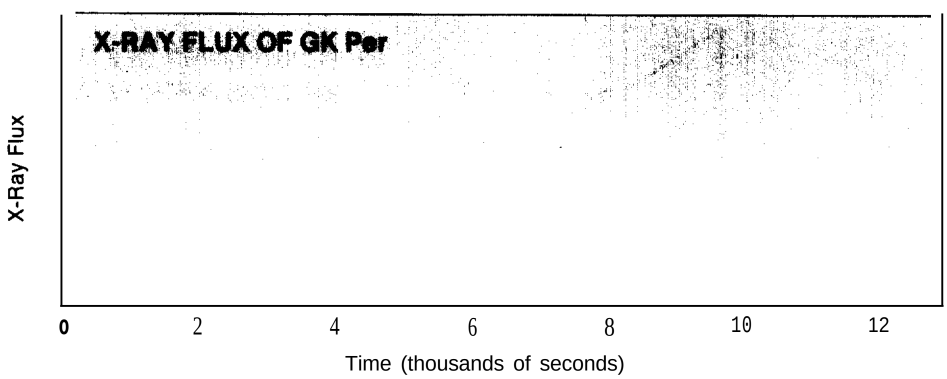


Fig. 18. Spectra of various high-energy sources showing the relative deficiency of x rays in gamma-ray bursts. The spectra of the black-hole candidates are those of LMC X-1 when its spectrum is softest (upper curve) and of Cyg X-1 when its spectrum is hardest (lower curve). The solar flare is one that occurred on June 7, 1980. The pulsing sources are the rotation-powered pulsar in the Crab Nebula (upper curve) and the accretion-powered pulsar Vela X-1 (lower curve). The x-ray burster is XB1724–30 at its hardest. The gamma-ray bursts were recorded (left to right) on May 14, 1972, July 31, 1979, October 16,1981, and January 25,1982.



◀ ***Fig. 19. A portion of the 2- to 10-keV x-ray light curve for the cataclysmic variable GK Per. The curve is approximately a modulated sinusoid with a period of 351.341 seconds.***

Cataclysmic Variables

The x-ray binaries discussed so far are such rare objects (only about two hundred of them exist in our galaxy) that the statistical distributions of, say, their periods, masses, and galactic positions are difficult to determine. Also, because even the closest one is a long way away, they are difficult to observe at optical and radio wavelengths. Fortunately, we can supplement our understanding of neutron-star binaries in important ways by observing the more numerous and less distant cataclysmic variables.

These systems are low-mass close binaries—often x-ray sources themselves—in which the compact object is a degenerate dwarf rather than a neutron star. Although the masses of degenerate dwarfs are comparable to those of neutron stars, degenerate dwarfs are much less compact—in fact, the gravitational energy release per gram of accreting matter is a thousand times less than for matter falling onto a neutron star. Thus, cataclysmic variables tend to be less luminous. Even so, many cataclysmic variables will be easily observed by the high-sensitivity instruments being built for the XTE and ASTRO-C satellites (see "The Next Generation of Satellites").

Cataclysmic variables exhibit behavior analogous to the various neutron-star binaries: there are systems with large magnetic fields (10^6 to 107 G) that pulse strongly, systems that do not pulse, and even systems with quasiperiodic oscillations. Besides their evolutionary and phenomenological similarities to neutron-star sources, cataclysmic variables are interesting in their own right as examples of the behavior of matter under very different conditions of magnetic field, density, and spatial dimension. For example, cataclysmic variables show a "period gap'' —there are no systems with periods between 2 and 3 hours—a fact that has been attributed to the absence of magnetic braking of the orbital motion once the mass of the companion star falls below a critical value. It is not clear whether low-mass neutron-star binaries also show a statistically significant period gap, since so few such systems are known, but there are, indeed, no observed neutron-star systems with periods between 2 and 2.9 hours. In contrast to cataclysmic variables, however, there are also few neutron-star x-ray binaries with periods less than 2 hours.

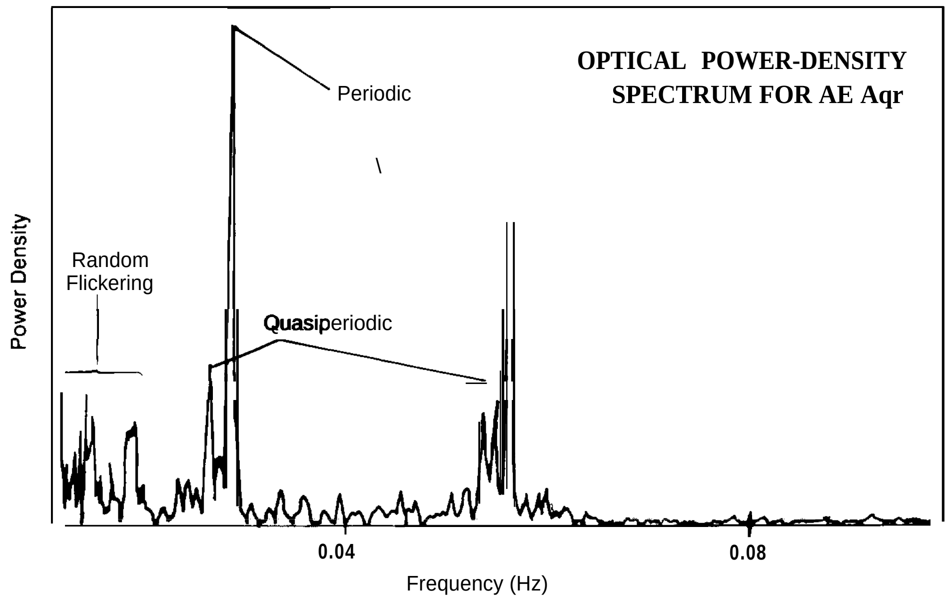
Strongly magnetic degenerate dwarfs are the analogues of accretion-powered pulsars: rotation of the degenerate-dwarf star causes the radiation to sweep periodically across the observer. One example is the cataclysmic variable GK Per, observed by EXOSAT during a large brightening. It has an x-ray flux curve that looks much like that of an accretion-powered pulsar (Fig. 19). Even the period of its pulsations, 351 seconds, is within the range of neutron-star sources. However, GK Per and other strongly pulsing cataclysmic variables have simpler x-ray flux curves than their neutron-star counterparts. The pulse waveform is nearly sinusoidal, lacking the high harmonic structure typical of accretion-powered neutron-star pulsars.

This simplicity is a result of the physical conditions at the degenerate dwarf. The radiating region is bigger, the plasma there is less dense, and the emission takes place in a much weaker magnetic field. Thus, the observed radiation beams are due solely to the shadowing of the emission region by the degenerate dwarf itself and not to the effect of magnetic fields. (Some cataclysmic variables-called AM Her stars—do have magnetic fields of about 10^7 G and show more highly structured periodic flux curves that are probably due to anisotropic absorption and emission in the magnetized plasma.)

Quasiperiodic oscillations, just discovered in bright neutron-star binaries (see "Quasipenodic Oscillations"), have long been seen in the visible light from cataclysmic variables (Fig. 20) and have even been seen in the x-ray flux from some of these sources. The oscillations observed in cataclysmic variables span a much wider range of frequencies, exhibit very different coherence times, and show a wider variety of frequency-intensity relations than do those observed in neutron-star binaries. As a result, interpretation of these oscillations is difficult, and no convincing explanation for them has yet emerged. Indeed, the different types of oscillations observed probably have different origins.

Comparison of quasiperiodic oscillations in neutron-star and degenerate-dwarf systems may help to shed light on the mechanisms at work, since the two types of systems provide different information. For example, analysis of oscillations in the visible light from cataclysmic variables is complicated because visible light represents only a small fraction of the energy output of the system (most appears as ultraviolet radiation). Moreover, the visible light comes partly from conversion into light of x rays falling on the disk and partly from radiation of heat generated inside the disk by shear. Thus, the visible light is not a good indicator of the accretion rate. In contrast, the x radiation from neutron-star sources is produced near the neutron star, is the dominant form of emission from the system, and is a good indicator of the accretion rate.

On the other hand, the visible light from some cataclysmic variables shows both quasiperiodic oscillations and periodic pulsations at the rotation frequency of the degenerate dwarf (Fig. 20). Thus, the study of cataclysmic variables may offer a test of the beat-frequency model in which quasiperiodic oscillations are attributed to the difference between the rotation frequencies of accreting matter in the inner disk and the rotation frequency of the star. Clear evidence of the rotation frequency of the underlying star in the bright neutron-star x-ray binaries that show quasiperiodic oscillations has yet to be seen.



▲
Fig. 20. ***Power-density spectrum of the optical emission from the cataclysmic variable AE Aqr showing narrow spikes that represent the first two harmonics of the degenerate-dwarf rotation frequency and smaller peaks at lower frequencies that represent concentrations of quasiperiodic power. The power density at very low frequencies varies greatly and arises*** from ***random flickering of the source.***

Black Holes

Are the compact objects in x-ray binaries all neutron stars and degenerate dwarfs or could some of them be black *holes?* The search for black holes in our galaxy has been disappointing. During the last ten years there has been a succession of black-hole candidates, most of which turned out to be strongly magnetic neutron stars, as eventually shown by the discovery of periodic pulsations. More recently, the source V0332+53, which showed the rapid flickering long thought to be a reliable signature of a black hole, was discovered to be a 4-second accretion-powered pulsar. Evidently, such flickering is a feature of neutron-star x-ray binaries as well. Though x-ray observations have not proved definitive, they can direct us toward black-hole candidates. For example, several candidates show, at least part of the time, an ultra-soft x-ray spectrum not seen in other objects. So far, the measurement of the masses of compact objects, using optical techniques, is the only reliable diagnostic for black holes (with reasonable assumptions, three solar masses is the theoretical maximum mass for a neutron star).

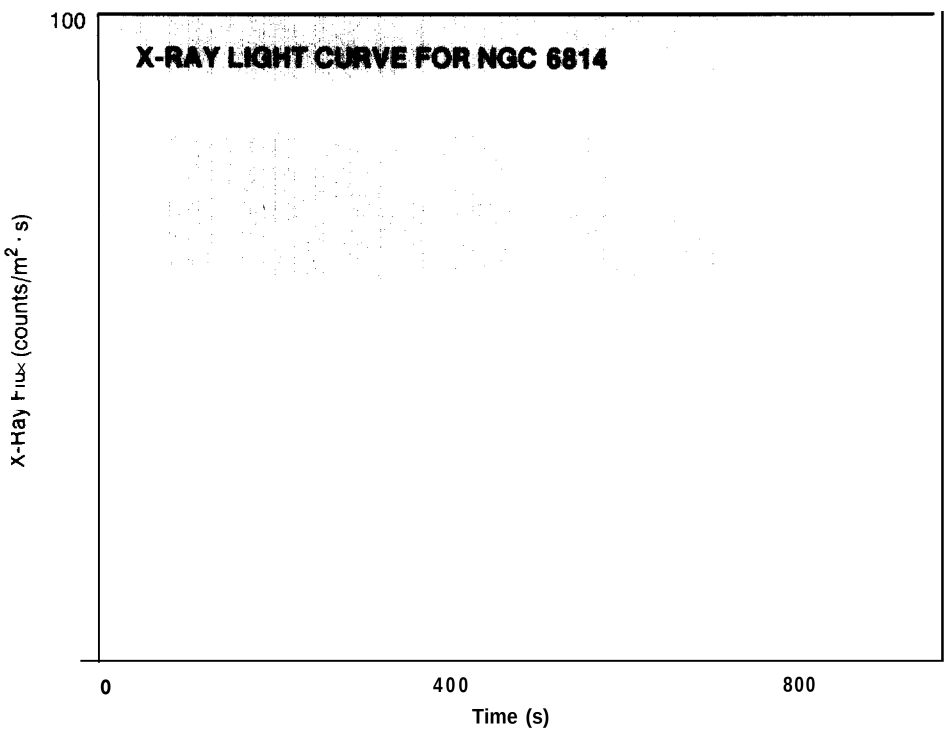
Currently, Cygnus X-1 and A0620–O0 are the only strong black-hole candidates in our galaxy: GX0339—4 is a more questionable one. The best candidate for a black hole at present is LMC X-3, a source in the Large Magellanic Cloud.

Active Galactic Nuclei. In contrast to the paucity of stellar-mass black holes, supermassive black holes are thought to be the engines powering most or all active galactic nuclei and quasars. X-ray and gamma-ray variability provide one of the few ways to probe the central regions of these objects. Interpreting the variability is much more difficult, however, because these systems are much less well understood.

Over 10^8 to 10^9 years an active galactic nucleus can radiate energy equivalent to a rest mass of 10^7 or more solar masses in the form of beams and clouds of relativistic particles. Even if energy conversion is very efficient, the mass of the engine driving this process is expected to be of the order of 10^8 solar masses.

One characteristic time scale for the variability of emission produced by matter swirling into a black hole is the time it takes light to travel across the innermost stable orbit—about 10^3 seconds times the mass of the black hole in units of 10^8 solar masses. If energy was generated by any other mechanism, the region emitting x rays would necessarily be much larger and such rapid variations might be unexpected. Figure 21 shows variations of the x-ray luminosity from the galaxy NGC

Fig. 21. The x-ray light curve for the active nucleus of the galaxy NGC 6814 showing fluctuations that vary rapidly enough to suggest that a black hole is the engine for this system. ▶



6814. Large fluctuations appear within a few hundred seconds, suggestive of the presence of a large black hole.

The instruments to be placed aboard ASTRO-C and XTE will be better able to measure variability and thus more fully elucidate the nature of the energy sources in active galactic nuclei. In addition, XTE will be able to measure the spectra of hard x rays up to 200 keV. These measurements will help clarify the nature of the relativistic plasma in the central regions of active galactic nuclei and the emission mechanisms operating there. This work will complement planned research at other frequencies, such as the radio-wave interferometry studies (using the Very Large Baseline Array) of the angular structure and variability of these systems.

Remaining Puzzles

The progress discussed here is encouraging, but there is no shortage of problems for XTE and ASTRO-C to tackle. The increased sensitivity, rate of data acquisition, extended spectral coverage, all-sky monitoring capability, and flexibility of the instruments aboard these spacecraft are essential for solving numerous unanswered questions. Here are a few.

What is the internal structure and temperature distribution of a neutron star?

Just how fast are the reversals of the torque in accretion-powered pulsars such as Vela X-1, and what do the reversals tell us about the accretion flow?

How do the spins and magnetic fields of the neutron stars in low-mass binary systems evolve? Are these neutron stars the progenitors of millisecond rotation-powered pulsars?

Since the brightest galactic-bulge sources have no known binary periods. are they really binaries?

What is the cause of the quasiperiodic oscillations in bright bulge sources? Do these neutron stars have magnetospheres?

Will a non-steady-state approach to the accretion of matter onto a neutron star explain the ratio of the mean luminosity of Type I x-ray bursts to the total luminosity of the sources? What fundamental property of low-mass binaries is yet to be revealed by the remarkable scaling behavior of Type II bursts?

What causes the periodic long-term variations seen in a variety of galactic x-ray sources? Are any of the models proposed so far correct?

Is free precession common among neutron-star x-ray sources? If so, what drives it and how?

What is the nature of the gamma-ray bursters? Do they have companions? Does accretion play a role?

What is the range of degenerate-dwarf magnetic fields in cataclysmic variables? What role does magnetic braking play in the evolution of such systems?

Where are the black holes of stellar mass?

What mechanisms are responsible for the x-ray and gamma-ray emission from active galactic nuclei and quasars?

Discovery in this field has hardly paused for twenty-three years. New instruments will sample many more sources while allowing us to study known sources in much closer detail. There is every promise that studies of time variability will further elucidate the nature of cosmic x-ray sources. Most exciting will be the discoveries we cannot anticipate but can only expect. ■

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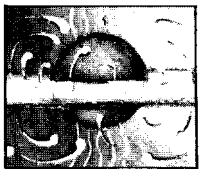


New Analysis Techniques

Coupled with the new satellites (see "The Next Generation of Satellites"), new analysis techniques will help reveal the underlying astrophysics in ever greater detail. Recently, for example, new methods of data handling have substantially improved the precision with which the orbits of pulsars in binary systems can be determined. As discussed in the section entitled "Pulse Timing" in the main text, precise determination of the orbit yields valuable information about key astrophysical questions, such as the masses of the pulsar and its companion, the internal structure of the companion, and the evolution of the system.

The principal method used to determine the orbit of a pulsar relies on measuring the changes in the arrival times at earth of pulses emitted by the pulsar as it moves around its orbit (Fig. 3 of the main text). The precision of such measurements is limited by fluctuations in the measured pulse shape caused by photon-counting noise and variations in the emission process, by the limited time resolution of the detectors, and by fluctuations in the spin rate of the neutron star.

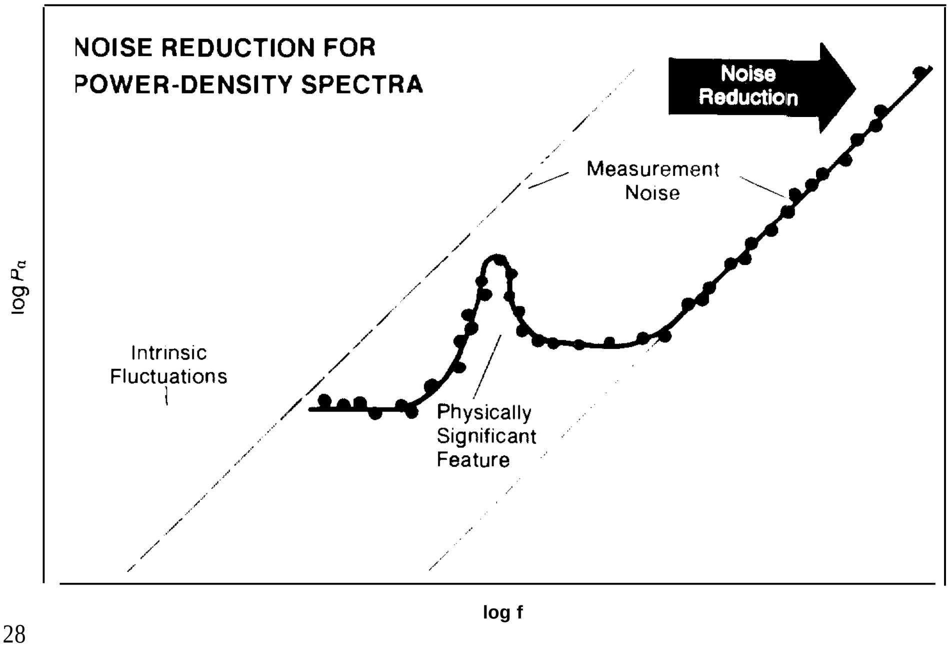
The large-area x-ray detectors on the next generation of satellites will provide very high counting rates (20,000 counts per second from bright sources) and make possible microsecond time resolution. This will greatly reduce fluctuations in the measured pulse shape caused by photon statistics and the imprecision in arrival times introduced by the finite time resolution of the detectors.

New analysis methods in which the pulse waveform is filtered have substantially reduced the uncertainty in pulse-arrival times caused by pulse-shape variations associated with the emission process. In a recent study of the accretion-powered pulsar Vela X-1, for example, filtering increased the precision of pulse-arrival times by a factor of two—equivalent to an increase in the area of the x-ray detector by a factor of four.

As the precision of pulse-arrival times is increased—by enlarging the detector area and filtering the pulse waveform—arrival-time variations caused by fluctuations in the rotation rate of the neutron star become more apparent (figurc). These spin-rate fluctuations can then be studied better, providing valuable tests of our understanding of neutron stars (see "Internal Dynamics of Neutron Stars").

For sources with unknown orbits, new algorithms will be needed to search efficiently for periodic and quasiperiodic oscillations in the x-ray flux. This is because the power in such oscillations is spread over a range of frequencies by the Doppler shift associated with the orbital motion of the source, making the oscillations difficult to detect. Thus, to find oscillations efficiently, new search algorithms must be developed that can quickly and systematically remove the effects of orbital motion for a wide variety of possible orbits.

New analysis techniques are also needed to uncover the origins of the large but erratic (aperiodic) variability seen in many compact x-ray sources. For example, fresh insights into the physical causes of this variability may be gained by applying the techniques recently developed to analyze nonlinear dynamical phenomena and chaos. ■



Schematic angular-acceleration power-density spectrum P.(f), showing the contributions made by spin-rate fluctuations and measurement noise. Here f is the analysis frequency. This example illustrates how a reduction in measurement noise can reveal a physically important peak in the spectrum of neutron-star spin-rate fluctuations. Measurement noise—caused by, say, the random nature of photon counting in the detectors—can be reduced by increasing the area of the detector or by using more powerful analysis methods, such as waveform filtering. Any such reduction uncovers more information about intrinsic fluctuations in the spin rate of the star and thus reveals more about their physical cause.

Internal Dynamics of Neutron Stars

The central element of many binary x-ray sources is a neutron star. Advances in the theory of dense matter, spurred by precise measurements of changes in spin rates of both rotation-powered and accretion-powered pulsars (see, for example, the section entitled "High-Mass X-Ray Binaries" in the main text) has made it possible to build detailed models describing the properties of these stars. The latest work has led to a dramatic reversal of earlier views.

Theory

From theoretical considerations, neutron stars are thought to consist of several distinct regions (Fig, 1). Immediately below the surface. the matter consists of a solid lattice of more or less ordinary atomic nuclei. As one moves inward to higher densities, however, the protons in the nuclei capture electrons to form neutron-rich nuclei. Above a certain critical density (about 4 x 10^{11} grams per cubic centimeter), called the *neutron drip point.*. it is energetically favorable for some neutrons to be outside nuclei. At these densities the lattice of nuclei is therefore interpenetrated by neutrons, which are believed to be superfluid. At still higher densities (above about 2.4 X 10^{14} grams per cubic centimeter—a lithe below normal nuclear density) the nuclei dissolve completely, leaving a dilute plasma of electrons and superfluid protons in the dense neutron liquid of the core.

In a rotating neutron star the neutron and proton superfluids are expected to behave differently. In both the inner crust and the core the neutron superfluid is thought to rotate by forming arrays of microscopic vortices. These arrays tend to rotate at the same speed as the core. In the inner crust it may be energetically favorable for the neutron vortices to pass through the nuclei of the solid lattice. If this arrangement is sufficiently favorable. the array of vortices will remain fixed in the lattice and will not be able to adjust to changes in the rotation rate of the cure. In this case the vortices arc said to be *pinned* to the lattice. If the rotational disequilibrium becomes large enough, the constant jiggling of the vortices will cause some to jump from one nucleus to another. This process is called *vortex creep.* As the rotational disequilibrium builds up, the dynamical forces on a vortex line may exceed the pinning force, causing it to suddenly unpin and move closer to its equilibrium position.

Unlike the neutron superfluid. the proton superfluid is affected by magnetic flux. The magnetic flux in this superfluid is confined to microscopic flux tubes around which proton currents circulate, These flux tubes are much more numerous than the vortices that form due to fluid rotation.

How these various components of a neutron star couple is not well understood, but such coupling determines how the star responds to changes in the rotation rate of the crust. The coupling of the electron and proton fluids in the core to each other and to the solid lattice is thought to be relatively strong, so that one of these components responds to changes in the rotation rates of the others within hundreds of seconds, depending on the rotation rate of the star and whether a strong magnetic field threads the crust and the core. On the other hand, a long-standing view; has been

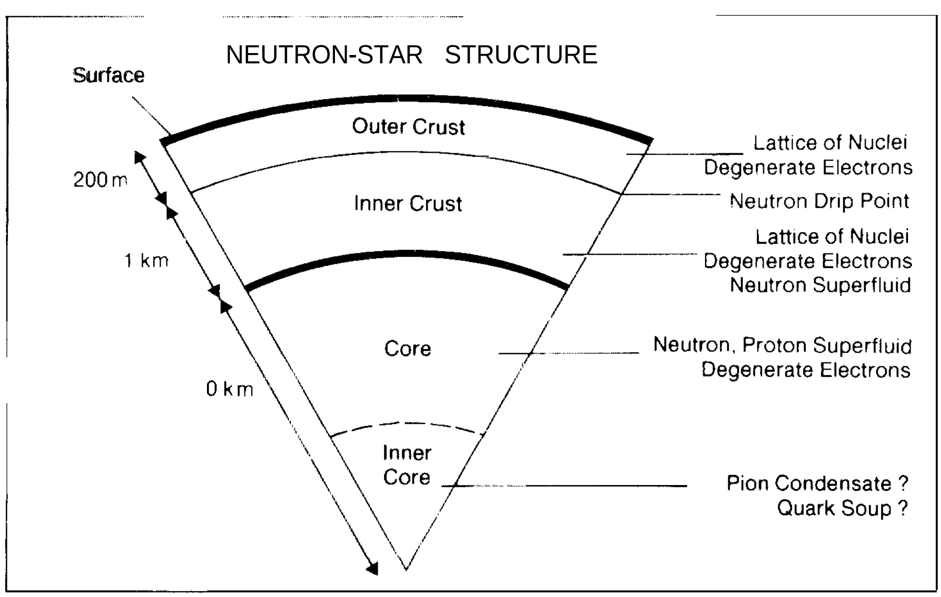


Fig. 1. The outer crust of a neutron star consists of a solid lattice of nuclei embedded in a sea of relativistic degenerate electrons. The surface of the crust may be solid or liquid, depending on the temperature and the strength of the surface magnetic field. The inner crust is a solid lattice of nuclei embedded in a sea of superfluid neutrons and relativistic electrons. The core is largely a superfluid neutron liquid with a slight admixture of degenerate electrons and superfluid protons. In heavier stars there may also be a distinct inner core that consists of a pion condensate or perhaps a quark soup. Characteristic dimensions are shown. ➤

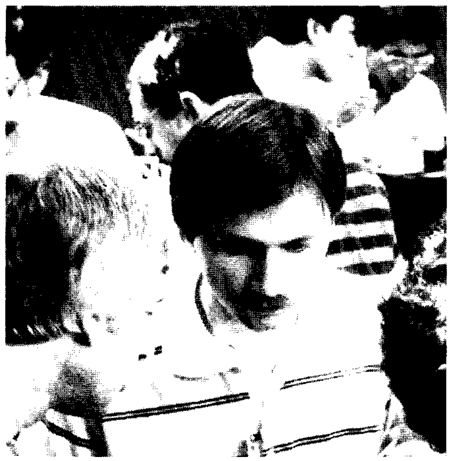
that the neutron superfluid in the core is only *weakly* coupled to the rest of the star, taking days to years to respond to changes in the rotation rate of the crust. To the extent that this is true, a neutron star can be idealized as consisting of just two components: the crust plus electron and proton fluids in the core, and the neutron superfluid in the core. This idealization has historically been called the *two-component model.* Recent theoretical work and observational data, which we will discuss shortly, has caused astrophysicists to dramatically revise this model.

Imagine forces on the neutron star crust that cause changes in its spin rate (see the section entitled "Pulse Timing" in the main text). Whether the forces are external or internal, whether the crust slows down or speeds up, the stellar interior must eventually adjust. This adjustment can be studied by monitoring the behavior of pulsars after the occurrence of sudden changes in the crust rotation rate. In some rotation-powered pulsars, isolated, relatively large jumps in the rotation rate, called *macroglitches,* have been observed. In both rotation- and accretion-powered pulsars, relatively small fluctuations in the rotation rate have also been seen. The statistical properties of these relatively small fluctuations have been modeled successfully as a series of frequent, small jumps in the rotation rate called *microglitches* (microglitches are thought to be too small to be seen individually with current instruments). The sizes and rates of occurrence of these glitches and the behavior of the rotation rate following them provide tests of models describing the dynamical properties of neutron stars.

Twelve macroglitches have been observed. The largest have occurred in the Vela pulsar (six events) and in three other rotation-powered pulsars (one event each). The smallest macroglitches were one-thousandth the size of the largest Vela macroglitch and occurred in the famous pulsar in the Crab Nebula (two events) and in another rotation-powered pulsar called 0525+21. No isolated events like these have been seen in accretion-powered pulsars.

Disturbing Results

For a decade, the model used to explain



the behavior of the star following a macroglitch was the two-component model. This model attributes the slowness of the observed recovery of the crust rotation rate, which takes days to months, to the relatively small torque exerted on the crust by the weakly coupled neutron superfluid in the core.

The two-component model appeared to explain the initial data on the post-macroglitch behavior of both the Vela and Crab pulsars. Although model parameters derived from fits to the data were different for the two stars, the parameters were approximately the same for macroglitchcs in the same star. However, recent detailed analyses of new observations of macroglitches have revealed complex post-glitch behavior not adequately explained by this model.

Further troubling evidence was provided by a detailed study of *microglitches* in the Crab pulsar. Like its response to macroglitches, a star's response to microglitches can be used to probe its internal dynamical properties. This is because the microglitches, which can be described as a random noise process, disturb the crust-superfluid system and may be considered an input noise signal applied to this system. The output noise signal, represented by changes in the rotation rate of the crust, is the input noise as filtered by the crust-superfluid system. In other words, the observed power at the analysis frequency f is given by

$$P_{obs}(f) = F(f)\ P_{in}(f),$$

where $P_{in}(f)$ is the power-density spectrum (Fourier transform) of the forces disturbing the crust, $F(f)$ is the power-transfer function, which reflects the dynamical properties of the neutron star, and $P_{obs}(f)$ is the observed power-density spectrum of fluctuations in the rotation rate of the crust.

Compared to the response times of the system, input forces are expected to be spiky, delta-function-like disturbances. The power-density spectrum of the fluctuating input forces is then a power-law ($P_{in} \propto f^{\alpha}$ for some constant α) over the analysis frequencies of interest. In fact, one can make $P_{in}(f)$ a constant (α= 0) by choosing to work with the power-density spectrum of the fluctuations in the right variable (which may be the phase, angular velocity, or angular acceleration of the crust). The shape of the key function $F(f)$ is then given directly by $P_{obs}(f)$. The shape of $F(f)$ can be used to distinguish between neutron-star models, for example, between a rigid-star model, in which the coupling between the crust and the core is strong, and the two-component model, in which the coupling is weak (Fig. 2). In particular, if a power-density spectrum of the fluctuations in the appropriate variable is flat, this indicates that the star rotates as a rigid body, or, if not, that any internal components are completely decoupled, for disturbances at the analysis frequencies observed.

Unfortunately, at high frequencies noise produced by measurement errors dominates (see the figure in "New Analysis Techniques"), making it difficult to tell whether or not the spectrum remains flat. At low frequencies the spectrum obviously cannot be extended to time scales longer than the observing time. Thus, data from a given experiment can constrain the moments of inertia of components with coupling times only in a certain range. Moreover, power-density estimates always have some uncertainty. Thus, even if the observed spectrum appears to be flat, only an upper bound can be placed on the inertia of components with coupling times in the range studied.

A recent analysis of optical timing data on the Crab pulsar showed that the spectrum of micro-fluctuations in angular acceleration is relatively flat over more than two decades in frequency. This result indicates that the neutron star is responding to microglitches approximately like a rigid body: for a coupling time of 10 days, no more than 70 per cent of the star's moment of inertia can be weakly coupled. These values are sharply inconsistent with the older values derived from fits of the two-component model to macroglitches. These older values implied that 95 per cent of the star's inertia is coupled to the crust with a coupling time of about 10 days. Thus, the two-component model cannot be an adequate description of the full dynamical properties of this neutron star.

Analysis of relatively small-scale fluctuations in the rotation rates of accretion-powered pulsars also shows no evidence of weakly coupled components. The most complete power-density spectrum is that recently obtained for Vela X-1 (see Fig. 5b in the main text), which covers periods from 0.25 to 2600 days. This spectrum implies that, for coupling times in the range of 1 to 30 days, no more than 85 per cent of the moment of inertia of the star can be weakly coupled.

THEORETICAL POWER-TRANSFER FUNCTIONS

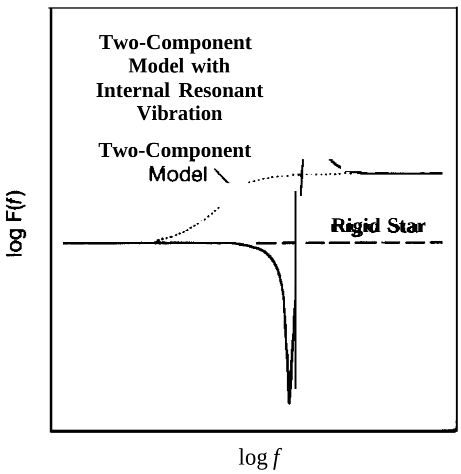


Fig. 2. Logarithmic plots of theoretical power-transfer functions F(f) for three distinct neutron-star models: a rigid star (dashed line), a two-component model (dotted line), and a two-component model in which the vortex array in the superfluid neutron core can be set vibrating (solid line). The shape of the power-transfer function depends on the coupling of the crust to the other components of the neutron star and therefore provides information on the nature of the star's interior.

New Ideas

The inability of the two-component model to account for the response of the Crab pulsar to both macroglitches and microglitches and the absence of evidence for any weakly coupled component in the microglitch data from the Crab pulsar and Vela X-1 have stimulated theorists to reexamine the view that coupling between the crust and the neutron superfluid in the core is weak. They found that a previously overlooked quantum liquid effect may account for the inability to detect a weakly coupled component.

As discussed above, the neutron superfluid in the core is expectcd to rotate by forming arrays of vortices, whereas the proton superfluid in the core is expectcd to rotate uniformly. Even though the neutrons are superfluid, their motion drags some protons around each neutron vortex. generating a proton supercurrent. (Because the drag coefficient is negative, the proton current actually circulates in the direction opposite to the neutron current.) At the very high proton densities in the core, this induced proton supercurrent generates a magnetic field of 10^{15} gauss (G) near each neutron vortex (even though the mean field in the star generated by this effect is only $10^{-7}/P$ G, where P is the rotation period in seconds). Because of this strong magnetization, the magnetic fields threading the neutron vortices scatter electrons very cffectively. causing a strong coupling between the core neutrons and electrons. The resulting short coupling time between the crust and the superfluid neutrons in the core (of the order of 400 P seconds) rules out gradual spin-up of these neutrons as the explanation of the long post-macroglitch relaxation times in the Crab and Vela pulsars.

If these theoretical results are correct. the only remaining candidate for a weakly coupled component is the neutron superfluid in the inner crust, where there is no proton fluid and the neutron vortices arc therefore unmagnetized. But the moment of inertia of this component is expected to be only about 10^{-2} that of the rest of the star. Thus, a neutron star in which only this component is weakly coupled would behave almost like a rigid body. consistent with the previously puzzling observations of the Crab pulsar and Vela X-1.

What then is the explanation of the macroglitches and the long post-glitch relaxation. which first suggested the idea of weak coupling between the crust and the

core of neutron stars? One possibility builds on the fact that the neutron vortices in the inner crust arc expectcd to bc pinned to the lattice of nuclei there. A macroglitch could be a sudden unpinning and movement of many vortices. causing a rapid transfer of angular momentum from the superfluid to the rest of the star and a jump upward of the rotation rate of the crust. If the neutron vortices in the inner crust are dynamically coupled to the crust by vortex creep, then the long relaxation could be explained as the response of this creep process to the macroglitch. This model differs from the two-component model in important ways. Only the neutron superfluid in the inner crust is involved and the superfluid response is fundamentally nonlinear, unlike the linear response given by the frictional coupling of the two-component model.

With relatively few parameters the vortex-unpinning model can explain the post-macroglitch behavior in the Crab and Vela pulsars as well as that in 0525+21. Because post-macroglitch relaxation is thermally activated in this model and hence the relaxation time is proportional to the *internal* temperature of the star, this temperature can be estimated from post-glitch timing observations.

Now if a neutron star is nearly rigid (the theoretical results described above imply that only one per cent of a neutron star is loosely coupled to its crust), the interpretation of the large pulse-frequency variations seen in accretion-powered pulsars becomes much simpler. Because internal torques can have only a small effect, any substantial fluctuations in the rotation frequency of the crust *must* be due to variations in the external accretion torque, that is, must be due to fluctuations in the torque exerted on the star by material falling onto it.

The theoretical arguments seem persuasive, but it is important to keep in mind that so far we have only a very modest amount of observational evidence. Although analyses of about two dozen rotation-powered pulsars are in progress. detailed microglitch power-density spectra have been published for only one rotation-powered and two accrction-powered pulsars, These spectra only exclude weakly coupled components with moments of inertia greater than 70 to 85 per cent of the star as a whole, for coupling times in the range of 2 to 20 days. Detection of a weakly coupled component with a moment of inertia as small as that expected on the basis of theory (about 1 per cent of that of the star) appears out of reach currcntly, but the upper bounds on the size of any weakly coupled component can be reduced substantially by more extensive observations using the large-area detectors planned for the near future (see “The Next Generationa of Satellites”). Moreover, measurements of a larger number of pulsars are essential before wc can be sure that our conclusions about neutron stars are not based on atypical examples. And, of course, there is always the possibility of yet another surprise. ■

Her X-1: Another Window on Neutron-Star Structure

Of all the x-ray binaries, none shows a more complex pattern of regular variability than Hercules X-1 (Her X-l). In this system, as in many others, a low-mass normal star transfers mass to a neutron star via a thin accretion disk. What makes Her X-1 so curious is its variability, which exhibits no less than three concurrent periodicities.

The general picture has been known since the first extensive observations were made by the x-ray astronomy satellite Uhuru over a decade ago. The fastest periodic variation is a stable 1.24-second pulsation. Two effects related to the rotation of the star probably play a role in producing this pulsation. First, because accreting matter funnels down the stellar magnetic field lines toward the magnetic poles. the emitted x rays are preferentially beamed in certain directions. The star's rotation sweeps these beams past us every 1.24 seconds in a manner analogous to the way the light from a lighthouse seems to pulse as the lamp assembly rotates. Second, because the orientation of the magnetic field with respect to the disk changes as the star rotates, the inward flow of mass, and hence the luminosity of the star, is likely to vary at the rotation frequency.

The pair of stars in the Her X-1 binary orbit each other with a 1.7-day period. This motion also modulates the x rays at earth by periodically obscuring them once per orbit when the neutron star is eclipsed by its companion.

The most interesting cycle is the 35-day one. The source follows a slightly irregular pattern in which it is bright for about 9 days and then relatively dim for about 26 days (figure). For years the most popular explanation for this 35-day cycle has been periodic obscuration by a tilted, twisted, and processing accretion disk. However, the cause of the tilt and precession has not been well understood. One popular explanation, that the companion star is processing (see the section entitled "Long-Term Periodic Variables" in the main article), has been questioned because the required precession of the fluid companion star has yet to be modeled successfully.

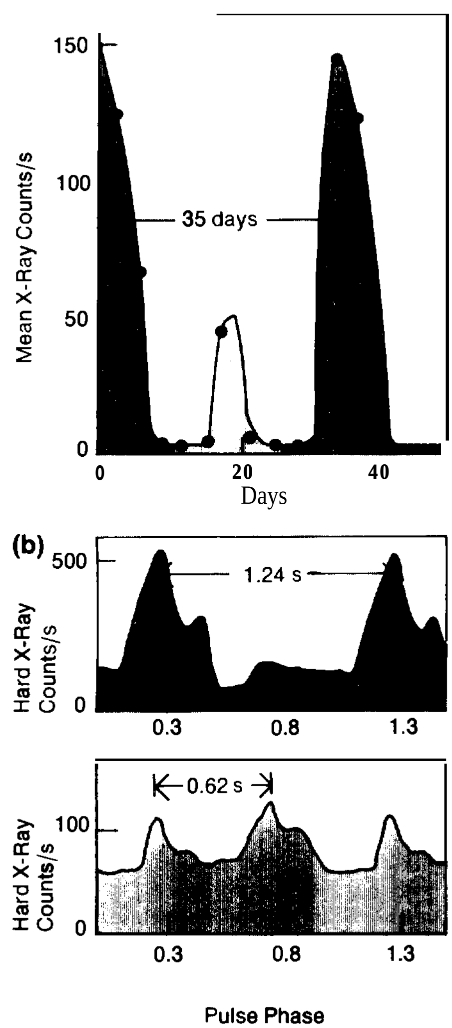
New studies by the EXOSAT satellite, reported at the Taos workshop, strongly support an alternative suggestion. In this study Her X-1 was monitored for hundreds of hours and approximately thirty times more x rays were recorded than in all previous studies put together. As a result, the pulse shape and its variation with the 35-day cycle were measured with unprecedented accuracy. These observations indicate that the neutron star itself is processing with a 35-day period.

The neutron star is expected to have two x-ray beams emanating from the two magnetic poles. If the neutron star does not precess, then the orientation of these beams relative to the rotation axis does not change, and the observed pulse pattern is constant. However, if the neutron star precesses, the magnetic poles, and hence the beams, drift with respect to the rotation axis, causing the corresponding peaks to appear or disappear from the observed pulse waveform.

The EXOSAT data indicate such a drift in Her X-1. During the bright phase of the 35-day cycle, we see a main peak at phase 0.3 coming from the pole that swings almost directly toward us. Six-tenths of a second later at phase 0.8, we see a hint of a peak from the edge of the opposite pole.

(a) Changes in the x-ray flux from Her X-1 (averaged over its 1.24-second pulse period) during one-and-a-half periods of the 35-day cycle. The bright state (red) lasts about 9 days. Midway between the bright peaks there is a smaller rise in intensity for several days (blue). (b) During the bright peak (red), the hard (1 to 30 keV) x rays show one large pulse every 1.24 seconds, revealing the neutron star's rotation. During the smaller, dim peak (blue), a second hard x-ray peak occurs *half a cycle later. This is evidence that the neutron star has precessed so that both magnetic poles sweep into view.* ▼

X-RAY FLUX FOR HER X-1



During the dim phase of the cycle, there are two almost equal peaks in the pulse pattern. In this case, it is thought that the magnetic poles have precessed so that both swing equally near us during the 1.24-second rotation. Neither comes as close as the pole producing the main peak did earlier, so neither resulting peak is as large as the main peak during the bright phase.

Precession of the neutron star also causes the pattern of x-ray flux falling on the near side of the companion star to vary with the 35-day period. This variation in the illumination of the companion star may introduce an asymmetry in the stream of material leaving the companion, causing the accretion disk to be tilted. Such a tilt leads naturally to precession of the outer rim, resulting in periodic obscuration of the x rays from the neutron star.

The idea that the neutron star in Her X-1 might be processing has major implications for two key aspects of neutron-star structure. First, it would imply that the super-fluid vortices in the inner crust (see "Internal Dynamics of Neutron Stars") are unpinned; otherwise, their gyroscopic motion would cause the star to precess far too rapidly. Second, it would indicate that the neutron star has a thick crust; otherwise, the star would not be sufficiently rigid to maintain its oblateness and hence could not precess fast enough. Detailed measurements of the 35-day cycle thus give us new insight into one of the most hidden parts of our universe-the intenor ofa neutron star. ■

Quasiperiodic Oscillations

In the spring of 1985, the phenomenon of Quasiperiodic oscillations was discovered by EXOSAT in the bright galactic-bulge sources GX 5-1, Cygnus X-2 (Cyg X-2), and Scorpius X-1 (Sco X-l). Such oscillations have now been looked for in more than a dozen other galactic-bulge sources, and four more examples have been found. Quasiperiodic oscillations are revealed in a power-density spectrum as a broad peak covering many frequencies rather than a sharp spike at one frequency. Moreover, in the bulge sources the position of this broad peak is seen to vary with time. and the changes seem to be correlated with changes in the source intensity.

For example, GX 5-1 has a broad peak in its averaged power-density spectra whose central frequency systematically increases from 20 to 36 Hz as the source intensity increases from 2400 to 3400 counts per second (Fig. 1). The peaks in Cyg X-2 and Sco X-1 change in frequency from 28 to 45 Hz and from 6 to 24 Hz, respectively.

All the GX 5-1 and most of the Cyg X-2 data for 1- to 18-keV x-ray photons show a strong positive correlation between the peak frequency and the source intensity. In Sco X-1 the oscillation frequency, at times, shows a strong positive correlation with the intensity of the 5- to 18-keV photons but, at other times, exhibits a weak *negative* correlation (Fig. 2). Whether the oscillations in Sco X-1 have the same origin as those in GX 5-1 and Cyg X-2 is not yet clear.

A variety of physical mechanisms have been discussed for the Quasiperiodic oscillations in these bright galactic-bulge sources, but, at the moment, the *beat-frequency* model appears the most promising. If this model is correct, the Quasiperiodic oscillation frequency is a measure of the difference between the rotation frequency of the neutron star and the orbital frequencies of the plasma in the inner disk.

The model assumes that a *clumped* plasma is accreting from an accretion disk onto a weakly magnetic neutron star. Such clumping can be caused by magnetic, thermal, or shear instabilities. Once formed, clumps drift radially inward and are stripped of plasma by interaction with the magnetospheric field. Plasma stripped from the clump is quickly brought into coronation with the neutron star and falls to the stellar surface, where it produces x rays.

Inhomogeneities in the stellar magnetic field cause the rate at which plasma is stripped to vary with time, which, in turn, changes the intensity of the x-ray emission. Unless the stellar magnetic field is axisymmetric, aligned with the rotation axes of the disk and star, *and* centered in the star, the interaction of' a given plasma clump in the disk with the magnetosphere is greater at some stellar azimuths than at others. Because the clumps of plasma and the magnetosphere arc rotating at different frequencies, the strength of the magnetic field seen by a given clump will vary at the beat frequency or one of its harmonics. causing the x-ray emission to vary at the same frequency,

A simple version of the beat-frequency model predicts power-density spectra that are very similar to the spectra observed for GX 5-1 and Cyg X-2 (Fig. 3). The theory also predicts that changes in accretion rate should cause a shift in beat frequency similar to that actually observed for these two bright galactic-bulge sources (Fig. lb), Moreover, the neutron-star rotation rate (about 100 Hz) and magnetic field strength (about 10^9 G) inferred from the beat-frequency model are consistent with previous theories that binary systems like GX 5-1 and Cyg X-2, when disrupted, produce the observed millisecond rotation-powered pulsars.

The most direct evidence in favor of the beat-frequency model would be detection of weak x-ray pulsations at the predicted spin rate. Though several sources have been examined carefully and pulsations smaller than 1 per cent would have been observed, regular pulsations in the sources that exhibit Quasiperiodic oscillations are yet to be seen. One explanation for the absence of strong pulsations is that the magnetic fields of these neutron stars are too weak (less than 10^7 G) to channel the accretion flow onto the magnetic poles. This, however, does not agree with the strength of 10^9 G inferred from the beat-frequency model, which is large enough to produce some channeling and x-ray beaming.

In the context of the beat-frequency model, there are three distinct physical effects that could prevent observation of pulsations at the rotation frequency of the star. Radiation pressure within the magnetosphere could be supporting the accreting plasma, causing it to settle over a large fraction of the star's surface. Evidence for this effect comes from analyses of the hard x-ray components, which yield emitting areas comparable to the star's surface area. The resulting broad x-ray beam would produce only weak modulation and then at relatively high harmonics of the rotation frequency. Any modulation might be further weakened by bending of the photon paths in the strong gravitational field of the neutron star.

QUASIPERIODIC OSCILLATIONS OF GX 5-1

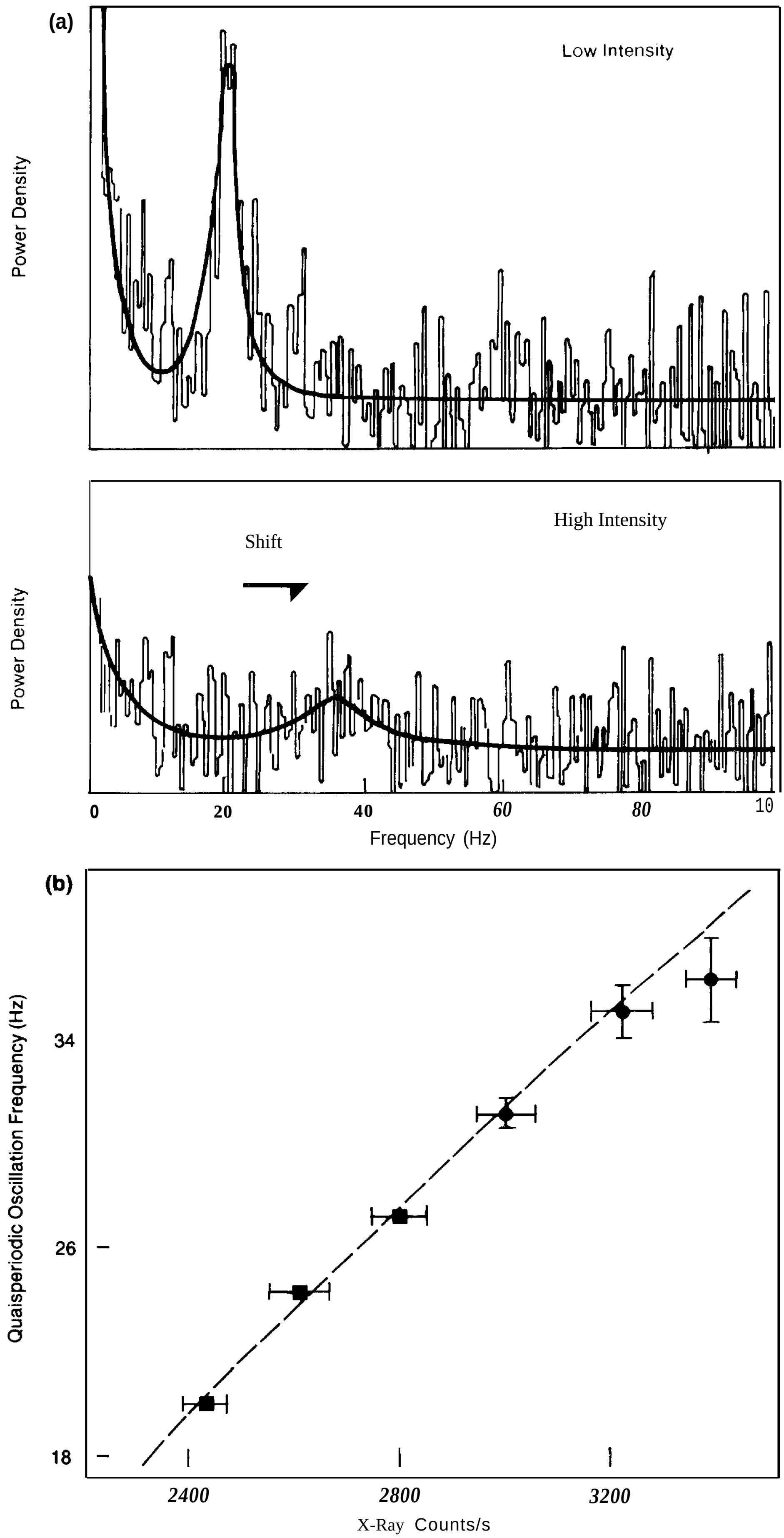


***Fig. 1.** (a) The Quasiperiodic oscillations of GX 5-1 are seen as a broad peak in averaged power-density spectra that shifts from 20 to 36 Hz as the intensity of the source increases. (b) A strong positive correlation exists between the centroid frequency of the Quasiperiodic oscillations and source intensity. The dashed line is the behavior predicted by the beat-frequency model.* ➤

The second effect has to do with the thick central corona that may be surrounding each bright galactic-bulge source. Analyses of the x-ray spectra indicate that these coronae may have dimensions on the order of 100 kilometers (about 10 neutron-star radii) and electron-scattering optical depths on the order of 10, which should drastically reduce the modulation due to x-ray beaming. In contrast, Quasiperiodic oscillations produced according to the beat-frequency model would not be affected if the mean time for photons to propagate through the corona is less than the oscillation period. Calculations for a typical system show that pulsations at the 100-Hz rotation frequency are strongly suppressed, whereas the amplitude of Quasiperiodic oscillations at 30 Hz is unaffected and is therefore equal to the modulation in the accretion rate.

Finally, there is evidence that the inner and outer parts of the disks of bright galactic-bulge sources are both geometrically and optically thick. Such disks would prevent us from seeing x-rays that come directly from the neutron star except when our line of sight is close to the star's rotation axis. X rays emerging near the rotation axis would, at most, be only weakly modulated.

Work currently underway on Quasiperiodic oscillations in galactic-bulge sources has benefited from previous work on this phenomenon in cataclysmic variables. In turn, the new observations and theoretical work may, when scaled appropriately, help us understand the oscillations observed in some of the cataclysmic variables. ■

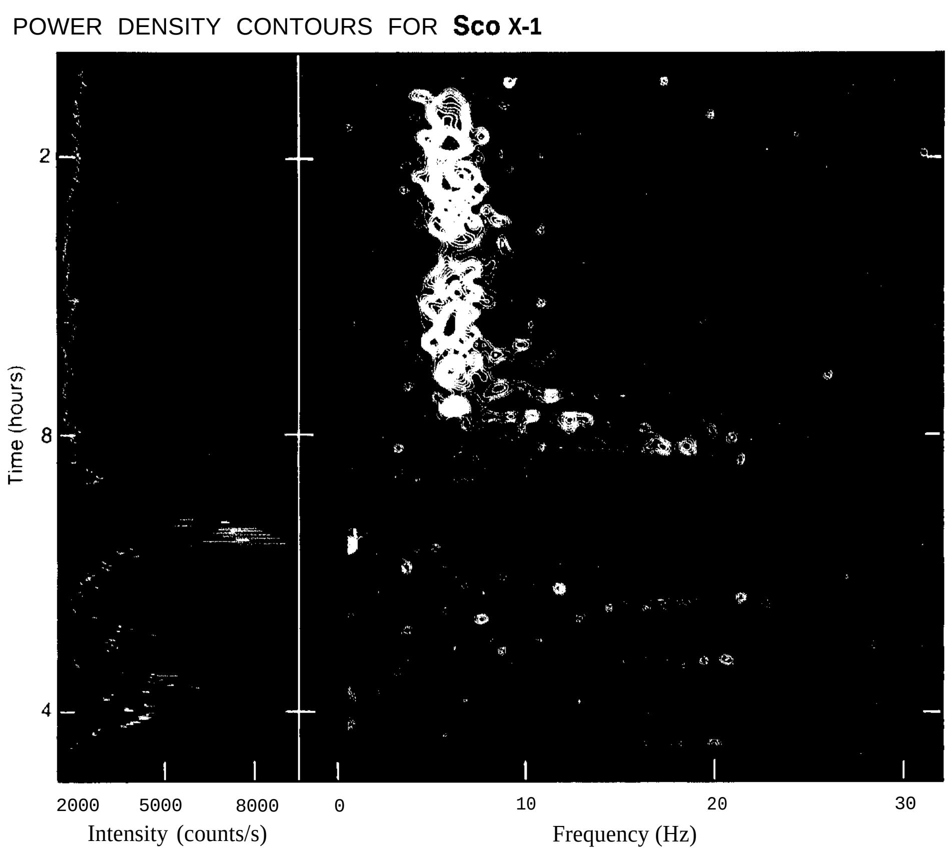


Fig. 2. Power-density contours for Sco X-1 as a function of time and frequency with high power in red, medium power in yellow, and low power in blue. The curve at the left is x-ray intensity as a function of time and shows flaring episodes (bottom) followed by an extended low-intensity state (top). The regions of concentrated color are the 6-Hz oscillations present during the extended low-intensity state. Power is spread over the range of 14 to 24 Hz between flares and at the start of the extended low-intensity state (horizontal clusters of blue circles). The gap in the data occurred when the detector was shut off for fear the intensity of the flare might damage the detectors.

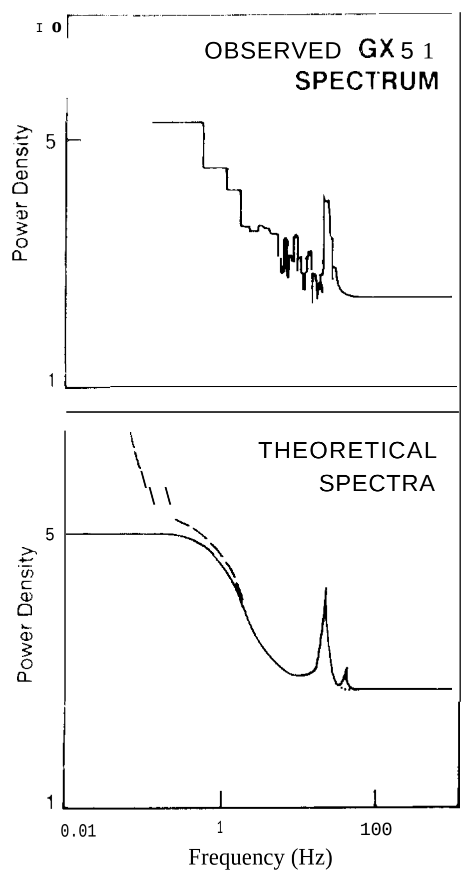


Fig. 3. An observed power-density spectrum for GX 5-1 (top panel) compared to two theoretical power-density spectra (bottom panel) calculated for the beat-frequency model using different parameter values. Because the low-frequency behavior of the two calculated spectra differ markedly, future observations should be able to constrain the values of the model parameters.

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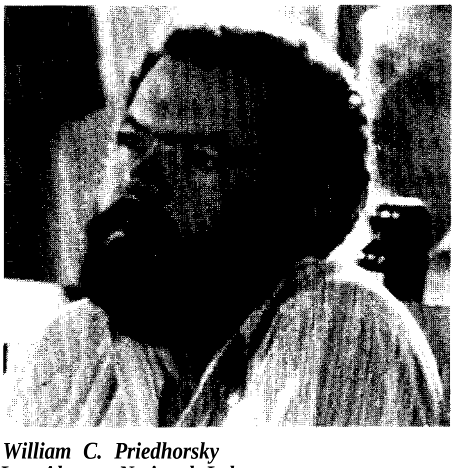

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