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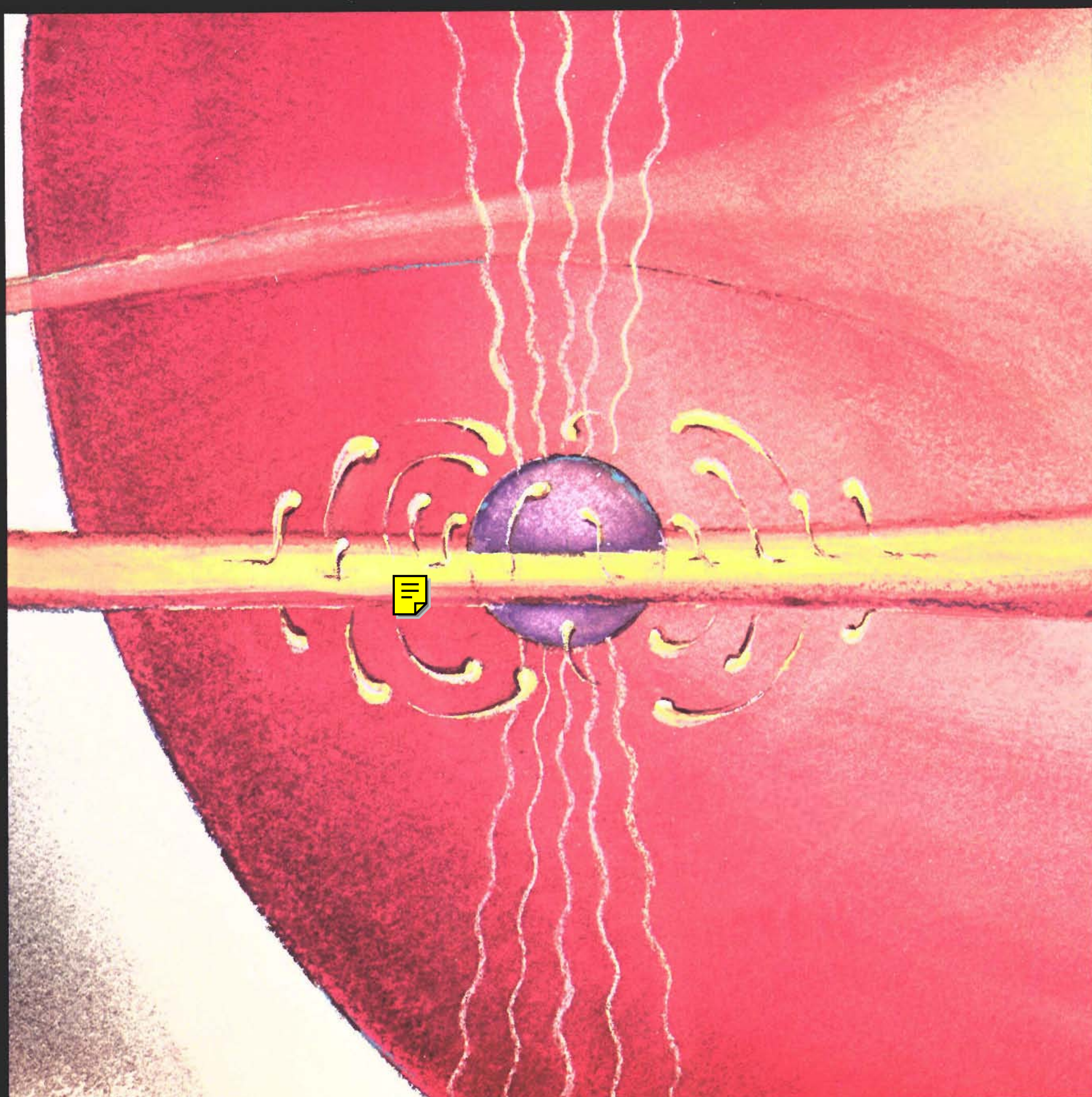
ASTROPHYSICS

Los Alamos Science

LOS ALAMOS NATIONAL LABORATORY



Inside This Issue

Los Alamos has long been a center of astrophysical research. After all, fission and fusion, explosion and implosion, shock waves and hot plasmas are key ingredients in both the physics of the stars and the physics of violent and controlled energy releases on earth.

Many astrophysicists at Los Alamos are occupied with the subject of this issue, the high-energy, high-intensity releases triggered by accretion of matter onto very dense stars. These objects (degenerate dwarfs, neutron stars, and black holes) are made of matter that has been processed by stellar evolution to a final collapsed state of extremely high density and very faint luminosity in the visible part of the spectrum. What makes some collapsed stars the hot spots of the universe is the fall of matter into their deep gravitational potential wells. The gravitational potential energy released by the fall is converted largely into x rays that signal the presence of these almost invisible objects.

As the x-ray universe has come into sharper and sharper focus over the last twenty years, it has become apparent that the process of accretion powers most localized x-ray sources, including pulsing and non-pulsing x-ray stars and the active nuclei of distant galaxies, the brightest of which are quasars. Accretion is the most likely way to explain the enormous energy output of these sources.

The fascination of localized x-ray sources is their dynamic evolution on human time scales. The normal visible stars in the universe change only very slowly, over millions and billions of years. Only by sampling many, each at a different stage of its life, can we infer their path from birth through the steps of thermonuclear burn that make them luminous. X-ray stars are different. Because the matter they contain is in such a concentrated form, physical processes are taking place at higher energies and on shorter time scales. Large variations in x-ray output occur within seconds, hours, days, and months and reveal an astonishing level of detail about the structure and dynamics of the sources.

"X-Ray Variability in Astrophysics," a summary of a Laboratory-sponsored workshop in Taos, New Mexico, last August, reviews the great advances that have been made in this field during the last decade. X-ray stars can now be sorted into well-defined categories: rotation-powered pulsars, accretion-powered pulsars that funnel accreting matter toward their magnetic poles and produce pulsing beams of x rays (see cover), accretion-powered non-pulsing neutron stars whose nature is obscured by coronae, and finally the less energetic but more numerous cataclysmic variables. All but the rotation-powered pulsars are binary star systems in which matter from a normal companion star falls toward a dense star. The information gleaned from bumps and glitches in the x-ray curves include details about neutron-star structure, patterns of accretion flow, sizes, masses, and relative orientations of the binary components, the strengths of magnetic fields, and the dynamics of x-ray bursts. Cyclotron lines in the spectra provide the first direct evidence for very strong magnetic fields (10^{12} gauss) near the surfaces of neutron stars. Accurate measurements of small changes in the frequencies of pulsars reveal the neutron star as a rigid structure that speeds up and slows down in response to changes in accretion flow. Apparently such flows can reverse direction in times as short as three days! The workshop report is filled with these and other surprising discoveries. As a warm-up to this stimulating but intensive discussion of current developments, the reader may appreciate being reminded of the early history of this field.

X-ray astronomy began with the space age, when rockets carried detectors above the x-ray absorbing layers of our atmosphere. The first experiments were done in the 1940s with captured German V-2 rockets that had been brought to America after World War II and made available for research. By the end of the fifties, x-ray emission from the sun had been recorded throughout an eleven-year sunspot cycle. Since the x-ray luminosity of the sun is a thousand times less than its optical luminosity, detection of x rays from outside the solar system was considered very unlikely by all but a handful of astrophysicists. The possibility of trying became greater as space research was emphasized after the Soviets launched Sputnik in 1957 and the Soviets and Americans resumed atmospheric testing of nuclear weapons in the early sixties. Interest in monitoring the effects of weapon tests spurred the development of x-ray and y-ray detectors, which then led to the detection of high-energy radiation from cosmic sources.

On June 18, 1962, a rocket was launched from White Sands Missile Range with the express purpose of detecting x rays that might be produced by energetic solar particles impinging on the moon. As the rocket spun on its axis, the line of sight to the detector swept out a great circle. A large signal was recorded coming from the constellation Scorpius, a signal that represented an x-ray luminosity 10,000 times greater than the total luminosity of the sun. This first cosmic x-ray source, named Scorpius X-1, was mysterious indeed. Was it a localized or an extended source, a single star or a group of stars, or a cloud of gas around an invisible star? Was the enormous energy output due to explosion of a star, accretion onto a dense object, or simply thermal radiation from very hot matter?

By 1967 a dozen groups were engaged in x-ray astronomy, and more than thirty sources had been observed. Most seemed to be localized sources, probably collapsed stars. Six were associated with the large clouds of gas and high-energy particles that result from the supernova explosion of a massive star. A few were associated with galaxies millions of light-years away. The accretion of matter from a companion star onto a collapsed star was proposed early on as the energy source of x-ray stars, but this hypothesis was hard to verify. The short duration of rocket observations (five minutes or less for a single object) made it hard to detect the periodic variation of x-ray output that results from the orbital motion of a binary with a likely period of several days. Determining the nature of the collapsed star was also hindered because the theoretically predicted signatures of neutron stars and black holes were not widely appreciated at that time.

The situation was confused by the discovery of radio pulsars in 1967. These objects produce radio pulses with such incredible regularity and with such short periods (tens of milliseconds) that only the rotation or pulsation of a star can explain them. They were soon interpreted as rapidly rotating neutron stars powered by their own rotational energy. Neutron stars were presumed to form when massive stars collapse following supernova explosions. Conservation of angular momentum would lead naturally to their rapid rotation. Moreover, collapse of the star's magnetic field would result in magnetic fields sufficiently strong to produce intense radio waves and x rays. The discovery of a pulsar at the center of the Crab Nebula (a supernova remnant) in both radio and x-ray emissions proved the existence of neutron stars, which had been postulated back in the 1930s to explain supernovae. On the other hand, x-ray stars such as Scorpius X-1 did not seem to pulse, so their nature remained mysterious.

The nature of accretion-powered pulsars was revealed with NASA's launching from Kenya in late 1970 of the first x-ray satellite. It was named Uhuru (the Swahili word for freedom) in honor of Kenya's Independence Day, which coincided with the launch date. The longer observing times and more sensitive detectors provided by Uhuru allowed confirmation of the hypothesis that the energetic x-ray stars are neutrons stars in binary systems. Initial observation of the x-ray star Centaurus X-3 showed x-ray pulsations characteristic of a neutron star, but at a much lower frequency (once every 5 seconds) than the rotation-powered neutron-star pulsar in the Crab Nebula, which rotates once every 0.03 second. Since Centaurus X-3 was putting out the same energy as the Crab pulsar, its source of energy could not be rotational energy alone. However, theoretical calculations showed that such slow spin rates are to be expected for accretion-powered magnetic neutron stars and gave x-ray spectra qualitatively similar to that observed. Further observations revealed a variation in pulse frequency that itself was periodic. This variation was explained as the Doppler shift caused by orbital motion of the pulsar in a binary system, which, in turn, meant that the pulsar could be powered by accretion of matter from the companion star. Eclipses were also observed. Subsequent study of long-term variations in pulse frequency and optical identification of the companion confirmed that Centaurus X-3 is a binary system containing an accretion-powered neutron-star pulsar. Eventually, study of the orbital motions of similar pulsars and their companions allowed researchers to estimate the masses of these neutron stars. They found the masses to be about 1.4 solar masses, in good agreement with the theory of stellar evolution. (Energetic non-pulsing x-ray stars were also shown to have companions, and circumstantial evidence suggests that they are neutron stars, but as yet, there is no way to determine their masses.)

The successes of the early x-ray satellites included the discovery of the first accretion-powered pulsar, of evidence for the existence of black holes at the centers of some x-ray sources, and of x-ray sources well beyond our galaxy, sources at the centers of distant galaxies and sources that extend over entire clusters of galaxies.

We have gone into some detail about the early work on accretion-powered pulsars because it provides a backdrop to

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EDITOR'S NOTE

Editor's Note, continued

the new findings discussed at the Taos workshop. At what some regarded as the most exciting workshop they had ever attended, the greatest stir was caused by the recent discovery of quasiperiodic oscillations in non-pulsing x-ray stars. These stars are thought to be rapidly rotating neutron stars in which any pulsation that might be caused by rotation is washed out by x-ray scattering coronae. The first evidence for their rapid rotation is the quasiperiodic oscillations found in data taken by EXOSAT, the European Space Agency's x-ray satellite launched in 1983. The oscillations in x-ray intensity suggest the interaction of a rotating accretion disk with a more rapidly rotating magnetized neutron star. One interpretation is that the oscillation frequency is the beat frequency between the matter in a Keplerian orbit at the star's magnetopause and the star itself. The variation in oscillation frequency reflects the changing pattern of accretion near the surface of the neutron star where the x rays originate. This type of signal has been seen before in the less energetic x-ray output from cataclysmic variables (degenerate dwarfs that are accreting matter from a companion star). The existence of quasiperiodic oscillations provides for the first time a means to study phenomena occurring near the surfaces of these neutron stars. Moreover, the intrinsic rotation frequencies of the neutron stars inferred from the data suggest that when these binary systems are disrupted, the neutron stars become millisecond rotation-powered pulsars.

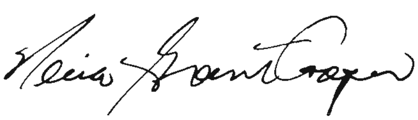
The other new data discussed at the workshop seem to explain the origin of the once-mysterious 35-day cycle in Hercules X-1. The neutron star in this accretion-powered pulsar may be freely precessing, causing its accretion disk to tilt and its x-ray output to vary. The rate of precession deduced from this interpretation implies new facts about the internal structure of the neutron star.

The deluge of data from the present generation of satellites and the promise of much more to come from the more sophisticated satellites now being planned in the United States and Japan are what prompted Laboratory staff members Richard Epstein and Bill Priedhorsky and University of Illinois professor Fred Lamb to organize the workshop. Their report of the proceedings reflects the excitement of the meeting and gives the reader an in-depth perspective of the progress and future direction of this rapidly advancing field.

A companion article is devoted to the most talked-about x-ray source of this decade—Cygnus X-3—which may be an accretion-powered pulsar enveloped in a scattering corona. The intense emissions at ultrahigh energies attributed to this source make it the first candidate for a localized source of the high-energy cosmic rays observed on earth. In addition, its tentative identification as a source of a previously unknown type of particle has captured the attention of particle physicists. In "Cygnus X-3 and the Case for Simultaneous Multifrequency Observations," France Córdova reviews the unusual behavior of this object not just at the high-energy end of the electromagnetic spectrum but at radio and infrared frequencies as well. In this way she illustrates the value of simultaneous measurements over a wide frequency range, a new approach to astronomy that is gaining wider and wider support.

France, a very careful observer, cautiously points out the large uncertainties in the evidence for new particles from Cygnus X-3, uncertainties that have only grown larger since the writing of her article. Scientists at the Laboratory and at many other institutions are mounting elaborate experiments to test the early evidence. Should it be confirmed, the implications are profound. It may mean, as Gordon Baym points out in "Does Cygnus X-3 Contain a Strange Neutron Star?", that neutron stars are not made of neutrons but instead are made of a quark soup containing a large fraction of strange quarks, the kind not found in ordinary nuclear matter.

Astrophysics is an arena to explore the most fundamental laws of physics. One of these, the conservation of angular momentum, is an important constraint on the accretion process powering x-ray binaries. In "Angular Momentum—The Cosmic Pollutant," Stirling Colgate and Albert Petschek explain how the conservation of angular momentum seems to prevent both the rapid accretion of matter in x-ray binaries and the condensation needed to form single stars. Though the authors intended only to remind the reader of this long-standing puzzle, their rethinking of the problem, complemented by new insights from the work of Wojciech Zurek and Willy Benz (see "Redistribution of Angular Momentum in Thick Accretion Disks"), may develop into a promising approach to its solution. Isn't that what science is all about? ■



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CONFERENCE REPORT

RESEARCH AND REVIEW

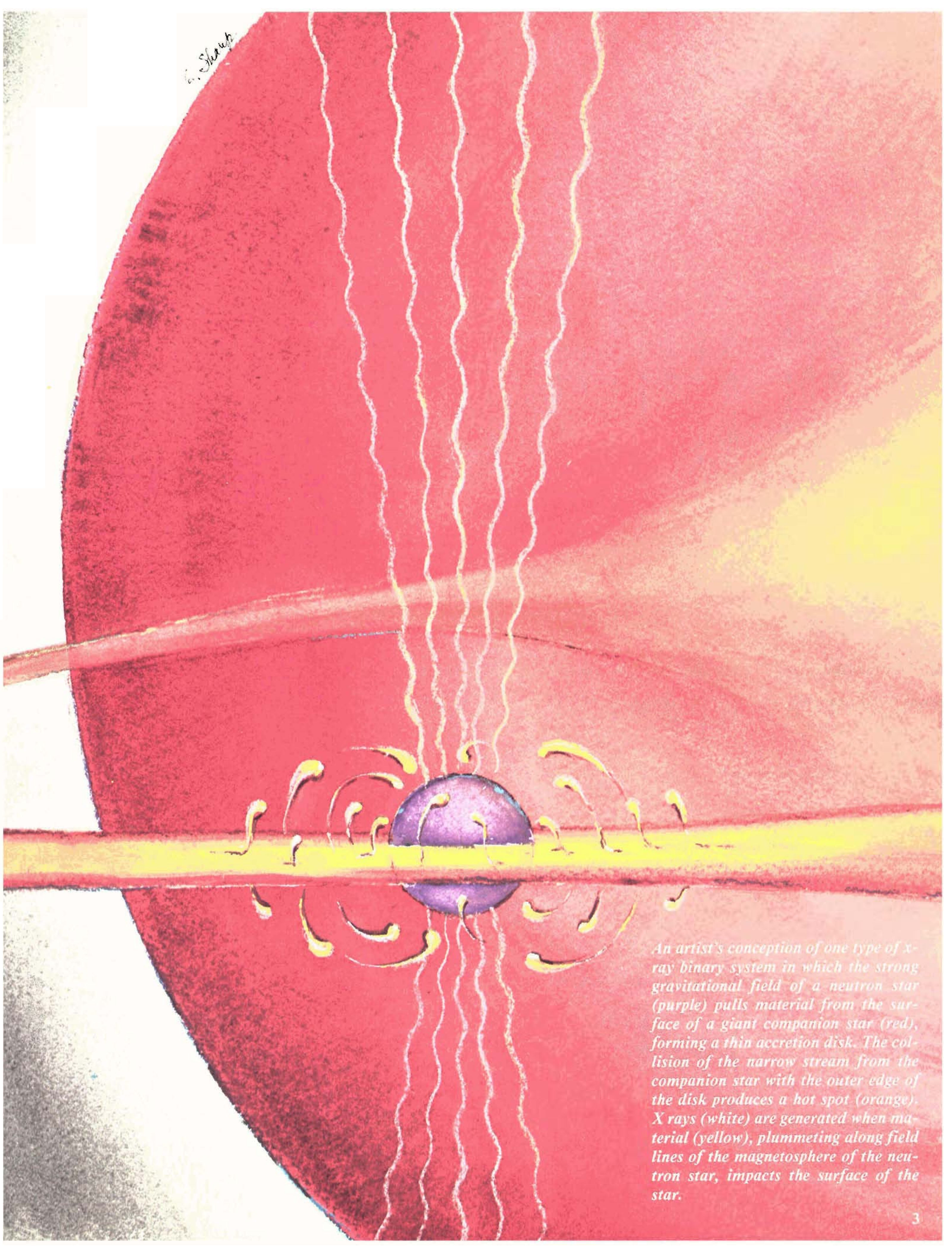
SCIENCE IDEAS

On the cover: Precise measurements of the time variability of x rays arriving at the earth reveal fascinating details about the nature of the sources that generate such radiation (white). The x-ray source here is a neutron star (purple) whose strong magnetic field interacts with material (yellow) that is falling toward it from a large companion star (red).

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

Workshop Photos by LeRoy Sanchez

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 precessing, 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

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 are adapted from material presented at the workshop. The selection of topics and the views expressed are 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

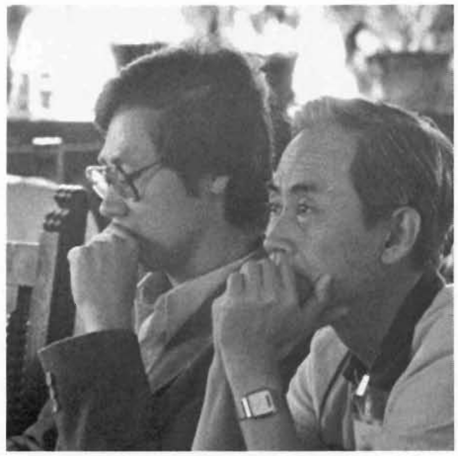
The brightest stellar x-ray source in our sky, Scorpius X-1 (Sco X-1), has been studied since the beginning of x-ray astronomy. The story of this object, discovered early but not easily understood, illustrates the development of x-ray astronomy.

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-1 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.

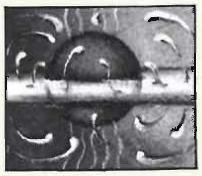
Sco X-1 has revealed its nature only grudgingly. The system is too small and far away for its components to be resolved;



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. *continued on page 8*



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 key 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 intensitites. 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 keV).

XTE will also carry a large-area (0.2-square-meter) hard x-ray telescope sensitive to energies from 20 to 200 keV 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 key 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.

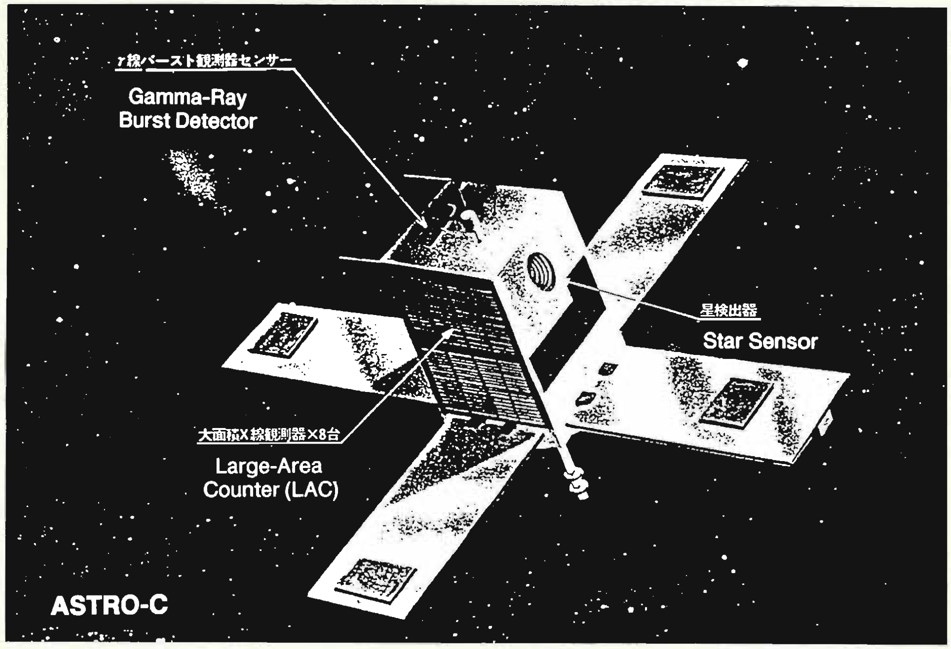


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Fig. 1. ASTRO-C, Japan's third x-ray astronomy satellite. The large-area counter (LAC) will consist of eight proportional counters containing a mixture of argon (70%), xenon (25%), and carbon dioxide (5%) and will be sensitive to x rays with energies 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

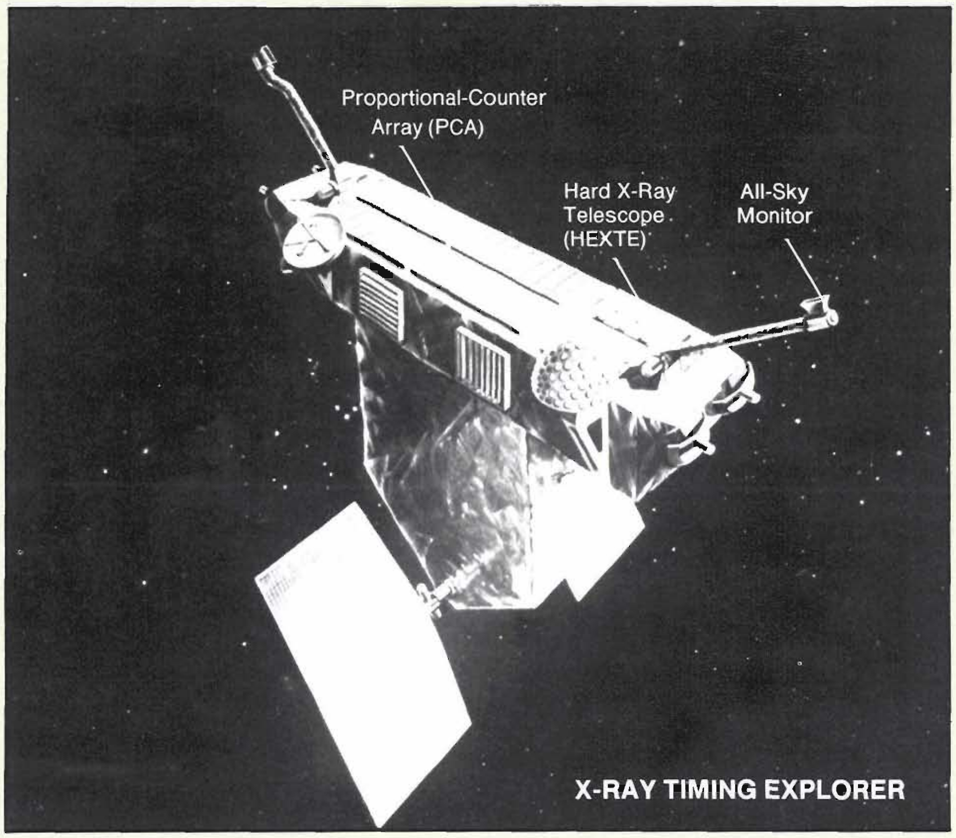

Fig. 2. NASA'S X-Ray Timing Explorer, or XTE. The observational objective of this satellite will be to measure photons from 2 to 200 keV on time scales ranging from 10 microseconds to months. To accomplish this objective, XTE will carry a 1-square-meter proportional counter (PCA), a 0.2-square-meter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

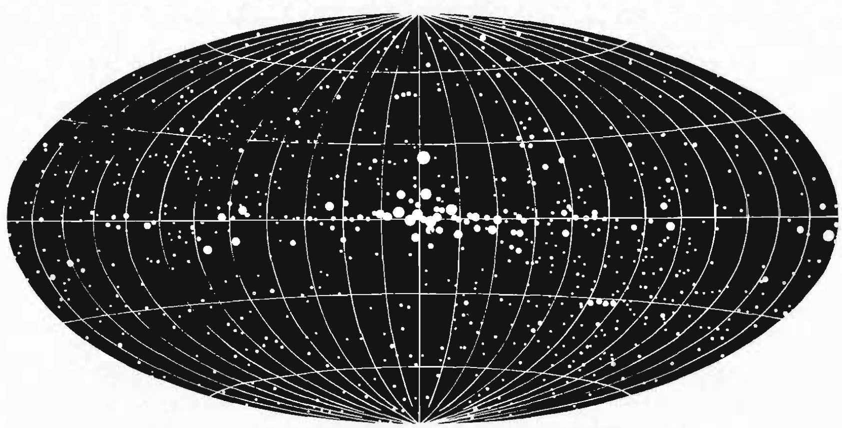

Fig. 1. A recent map of compact x-ray sources in our galaxy prepared using data from the A-1 x-ray experiment on board the HEAO-1 satellite. The radius of the dot representing a source is proportional to the logarithm of its intensity.

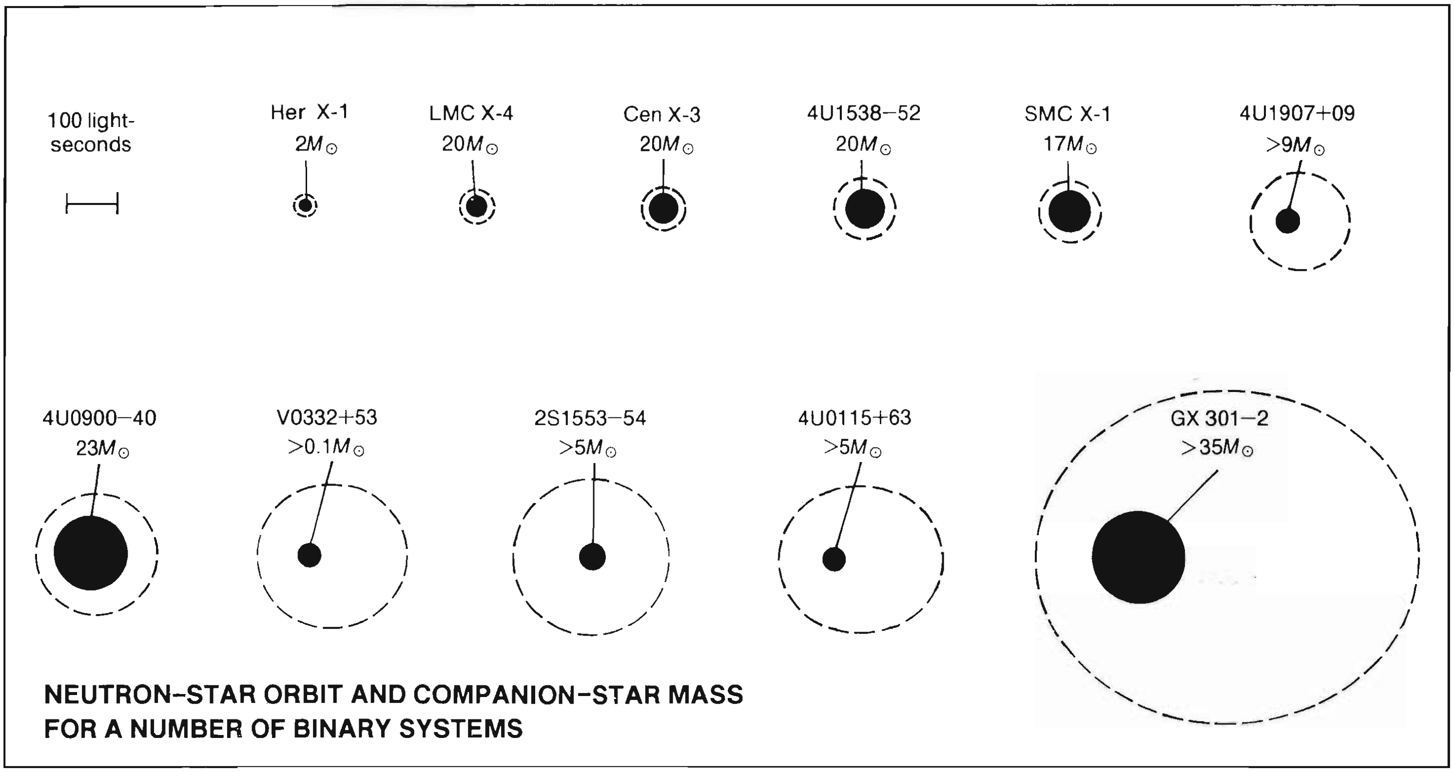

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Fig. 2. The neutron-star orbit and estimated companion-star mass (in terms of the solar mass $M_\odot$) for a number of binary systems. The mass of the neutron star is between ½ and 3 solar masses.

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 10^6 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 10^5 times that of the sun. In active galactic nuclei, dynamical time scales are as short as 10^2 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 2×10^{36} ergs/second).

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

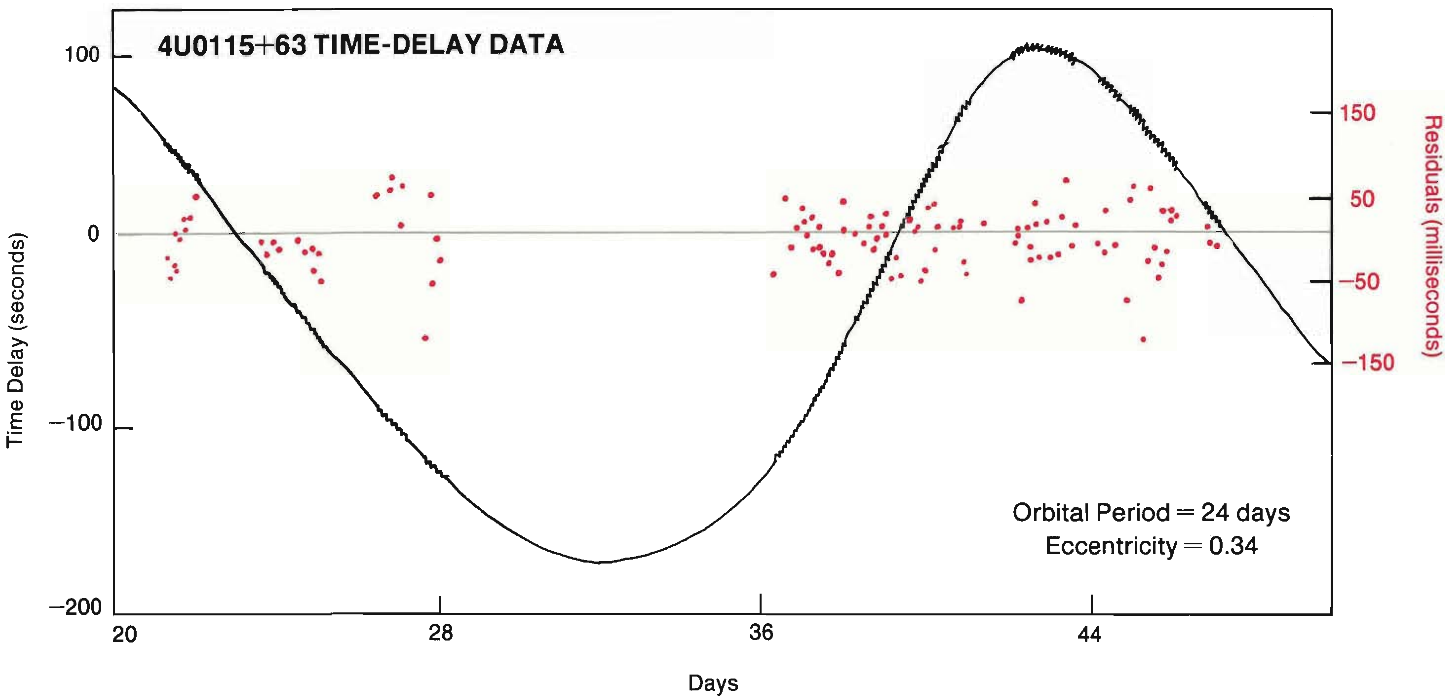

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Fig. 3. The orbital period and eccentricity for the 4U0115+63 binary system are obtained from a fit of time-delay data (black) after the effects of the motion of the satellite around the earth and the motion of the earth around the sun have been removed. 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").

INTRINSIC PULSE-FREQUENCY VARIATIONS

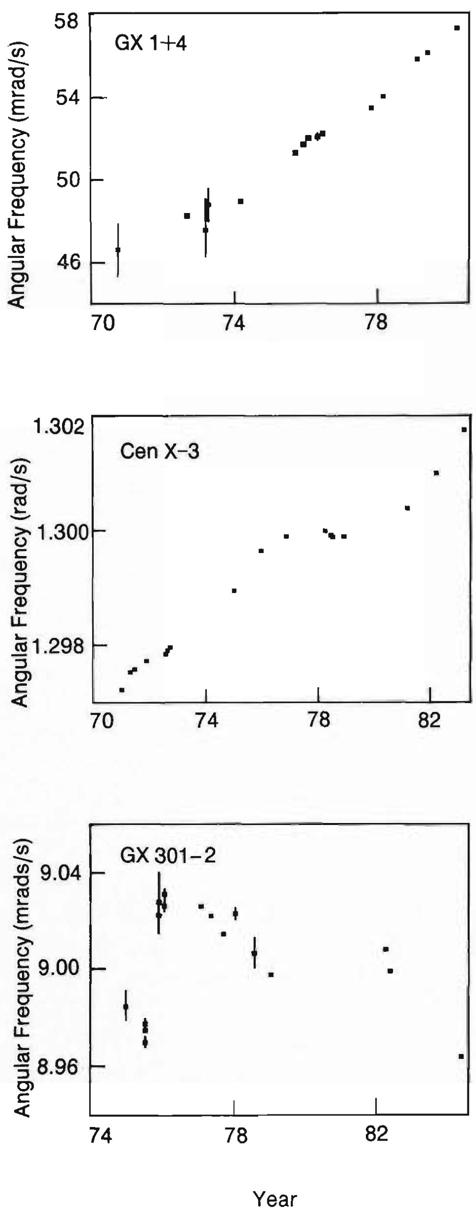

Fig. 4. Pulse-timing results for several accretion-powered pulsars, showing variations in the intrinsic pulse frequency that are most likely due to changes in the rotation rate of the neutron-star crust.

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.

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

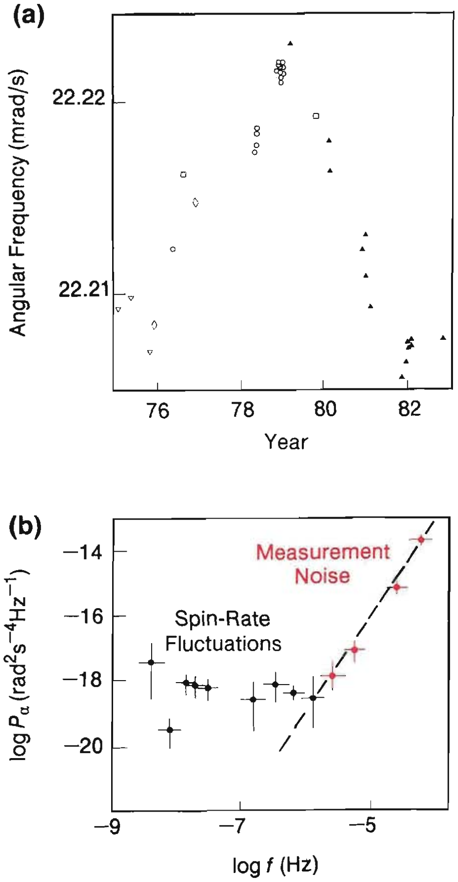

Fig. 5. Pulse-timing results for Vela X-1. (a) Although the change is small (0.5% overall), the pulse frequency, or angular velocity, of the neutron star appears to have increased from 1975 to 1979 and then decreased from 1979 to 1982. (b) The power-density spectrum of fluctuations in the pulse frequency 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 α 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

$$\alpha = n\,\mathring{M}_{\mathrm{m}}\,(G\,M\,r_0)^{1/2}/I\,,$$

where $\mathring{M}_{\mathrm{m}}$ 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 α and F? Suppose the observable x-ray flux F is proportional to $\mathring{M}_{\mathrm{m}}$. Now, the torque—and hence the angular acceleration—depends on the lever arm r_0, which becomes smaller as $\mathring{M}_{\mathrm{m}}$ increases. Thus, for disk flow, the expected correlation between α and F is

$$\alpha \propto F^{6/7}\,.$$

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

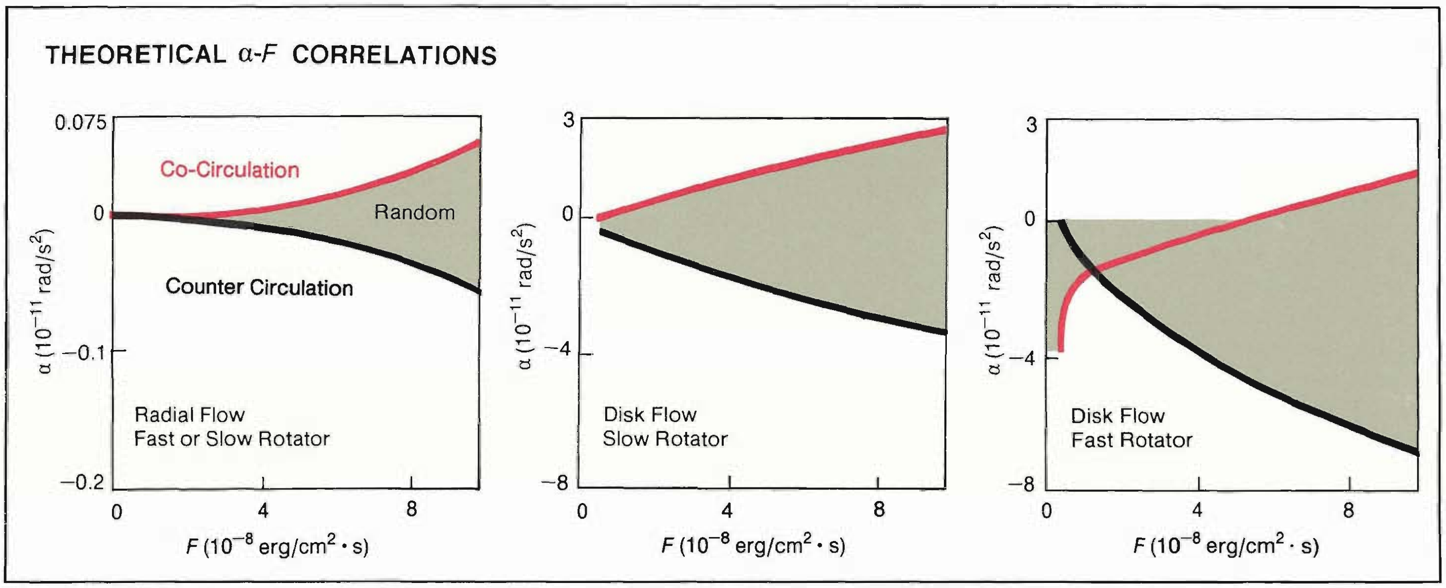

Fig. 6. Theoretical plots of angular acceleration versus x-ray flux (α-F) for various orientations of the angular momentum of the accreting matter. In all panels the red curve represents the case in which the circulation of the accreting matter has the same sense as the rotation of the neutron star, 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 α 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 α 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 α 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 α-*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 scatterings will, on the average, "blue shift," or increase, the photon energy. When the mean number of scatterings 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

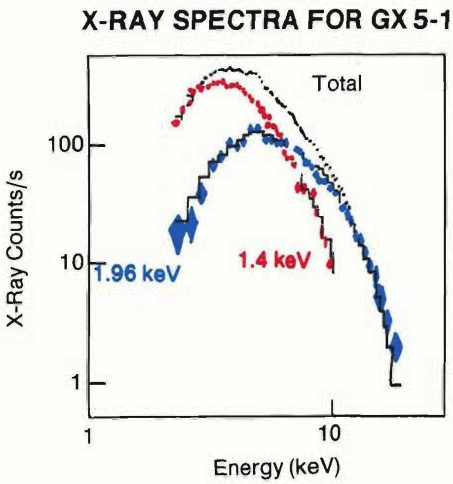

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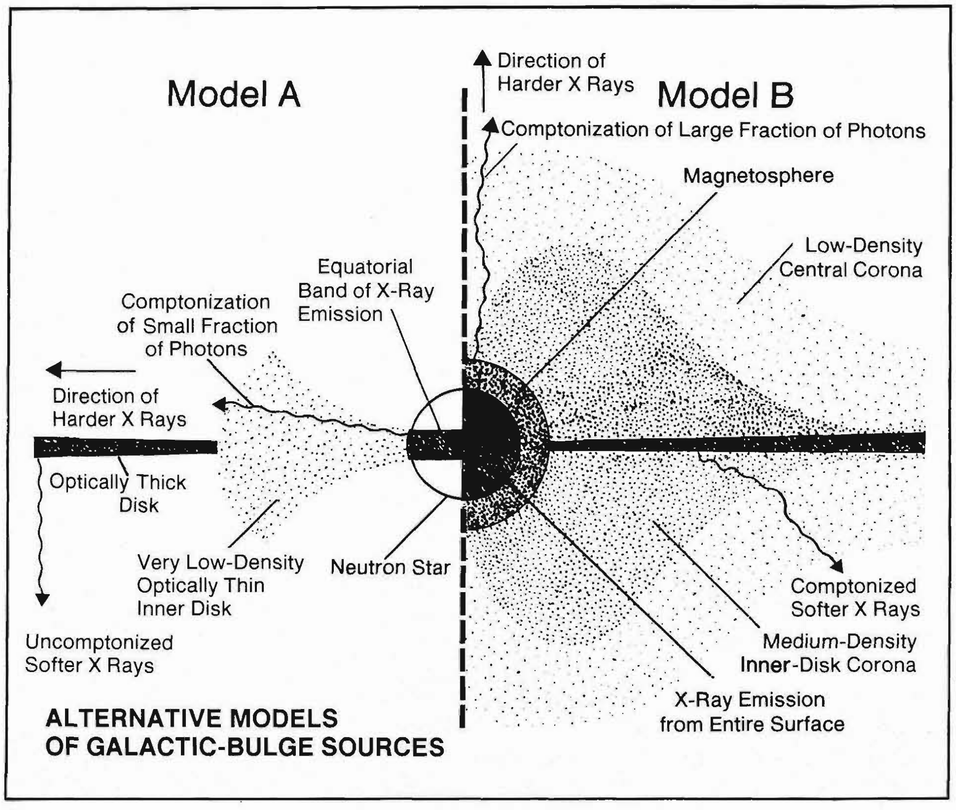
Fig. 7. X-ray spectrum (black) of the galactic-bulge source GX 5-1 decomposed into a softer (red) component (with a 1.4-keV blackbody fit) and a harder (blue) component (with a 1.96-keV fit). The fact that the softer x-ray component is constant in time whereas the harder component is variable allowed 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

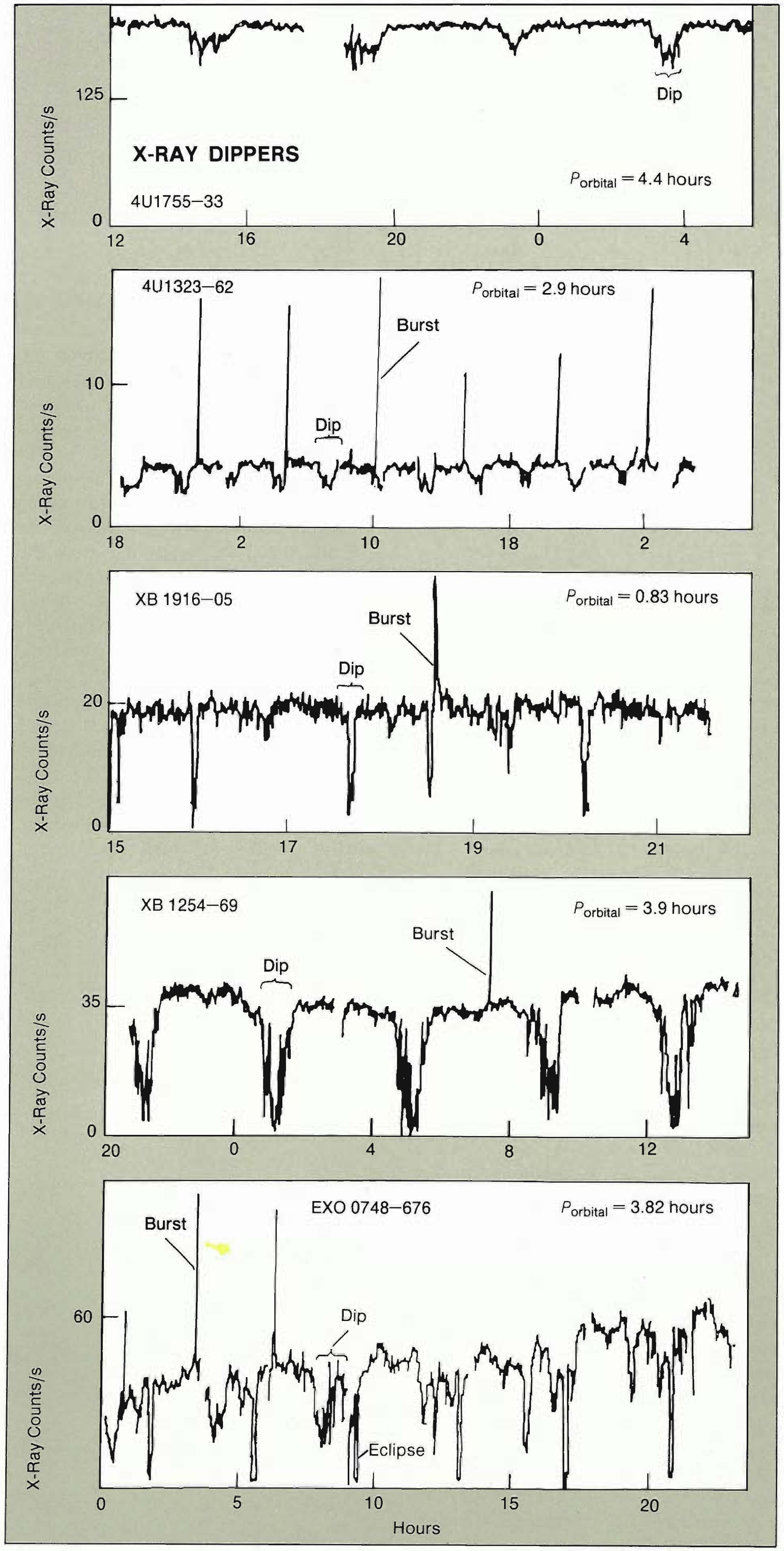
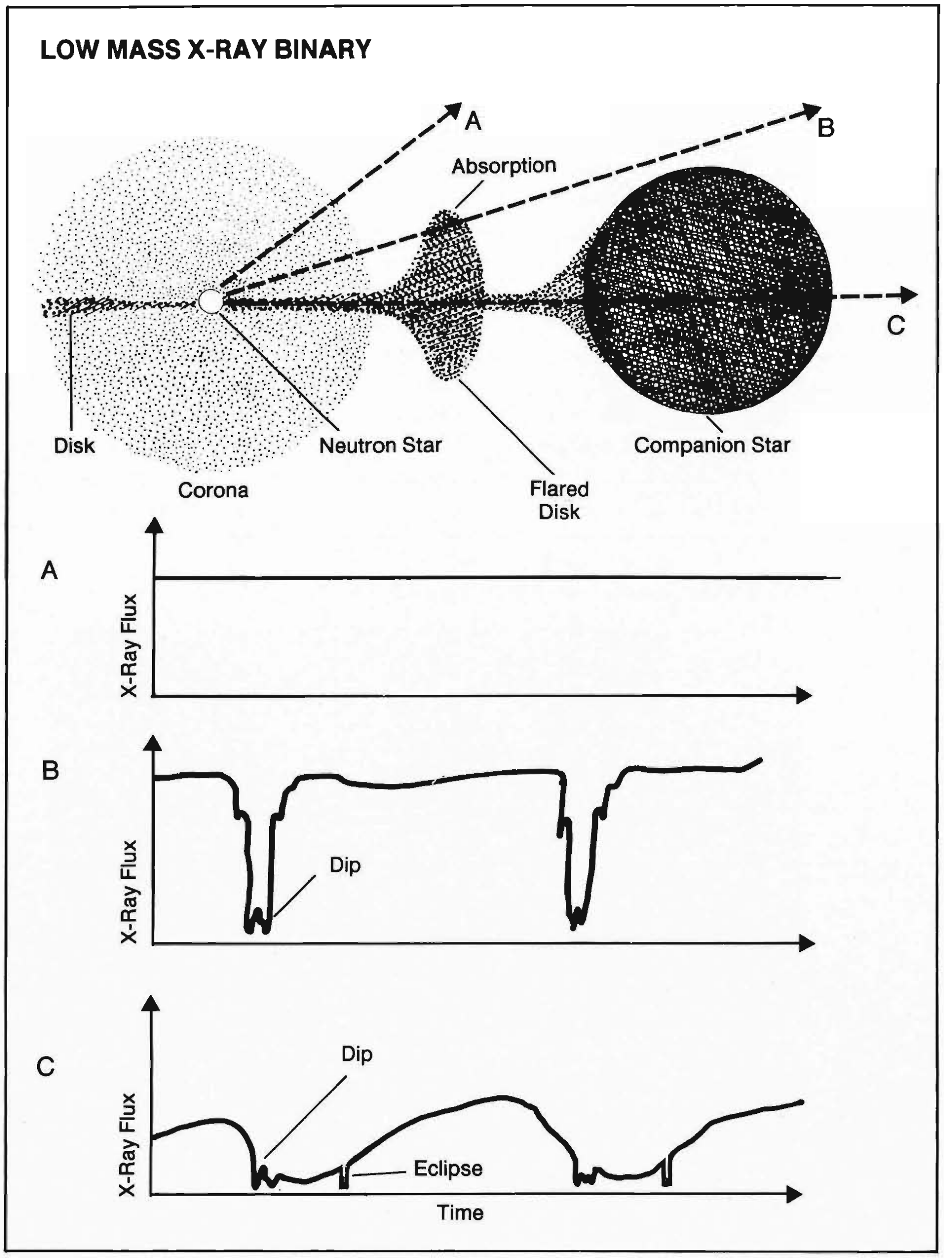


Fig. 9. X-ray light curves for five dippers whose orbital periods range from 0.83 to 4.4 hours. The bottom panel is an example of what is seen when the line of sight is close to the plane of the disk (view C in Fig. 10), whereas the upper panels illustrate what is seen when our sight line is above the 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, but 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 per cent.

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

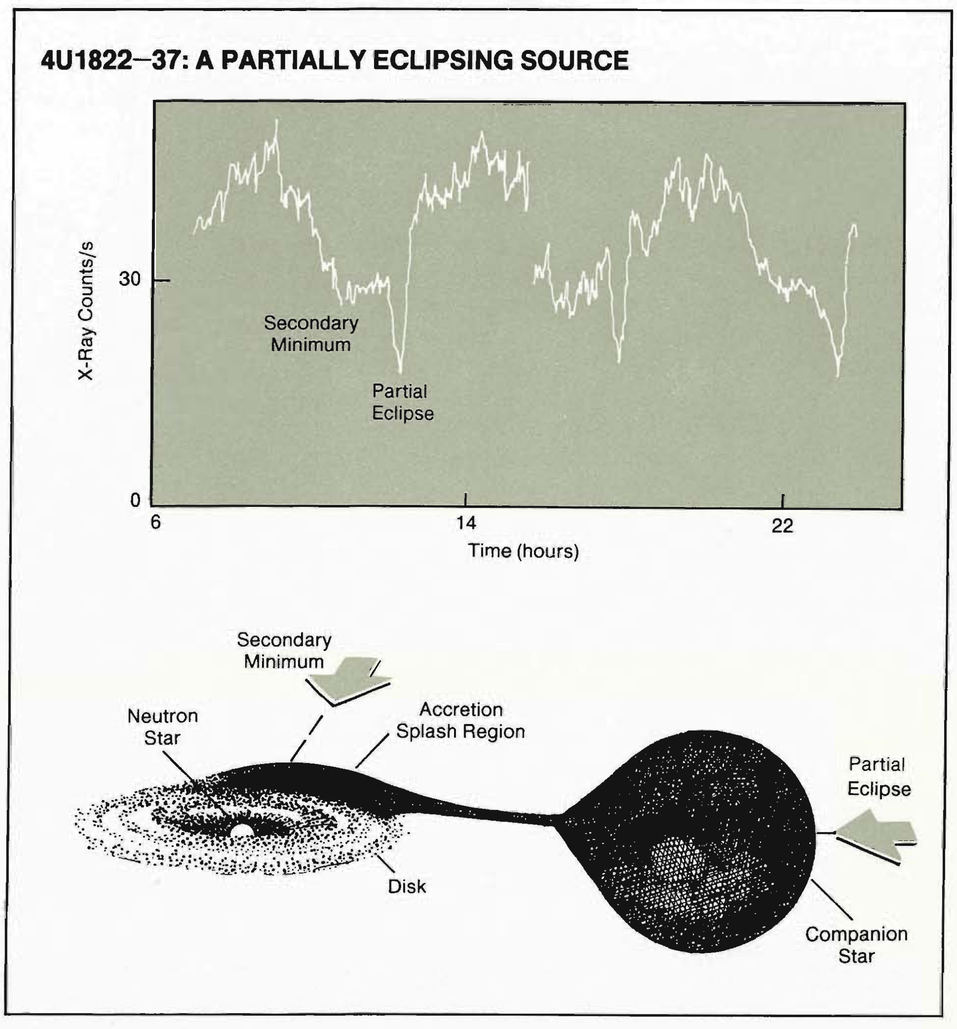
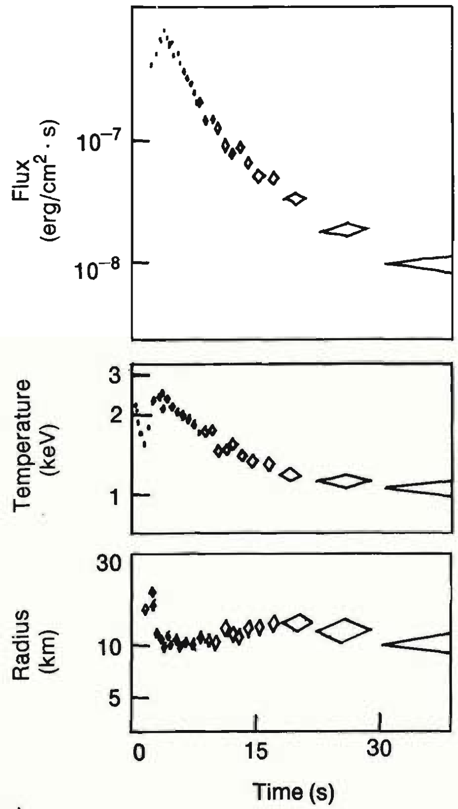


Fig. 11. ***X-ray light curve for 4U1822−37, a low-mass binary. The secondary minima in the data are most likely due to obscuration of the line of sight to the x-ray source by a thick region where the stream of accreting material hits the disk; the partial eclipse is caused by blockage of the line of 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



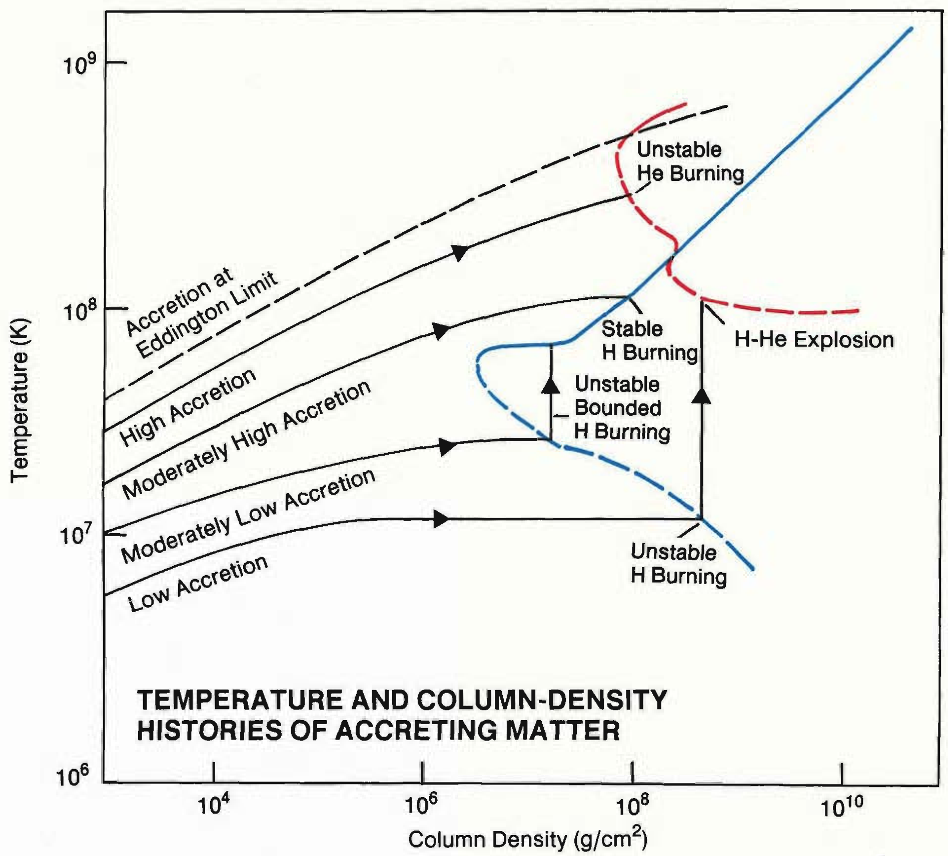
▲ ***Fig. 12. X-ray burst data for 4U1636—53, showing the hundred-fold variation in flux typical of such bursts (top) and the spectral temperature of the emission (middle). These two sets of data can be used to calculate the radius of the photosphere of the source (bottom), which, except for the initial 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

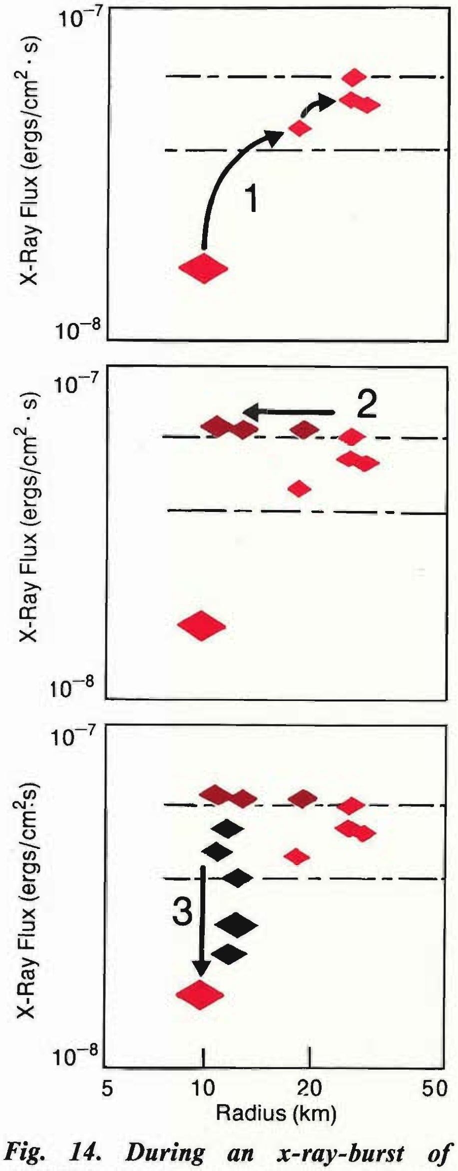


***Fig. 14.** During an x-ray-burst of 4U1636−53 the photosphere (and, hence, presumably the atmosphere) of the star expands (red) in two stages: once as the burst power reaches the limit for the outer hydrogen-rich layer, and again as the power reaches the higher limit for the helium-rich layer. Eventually, 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 II 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.

TYPE II X-RAY BURSTS

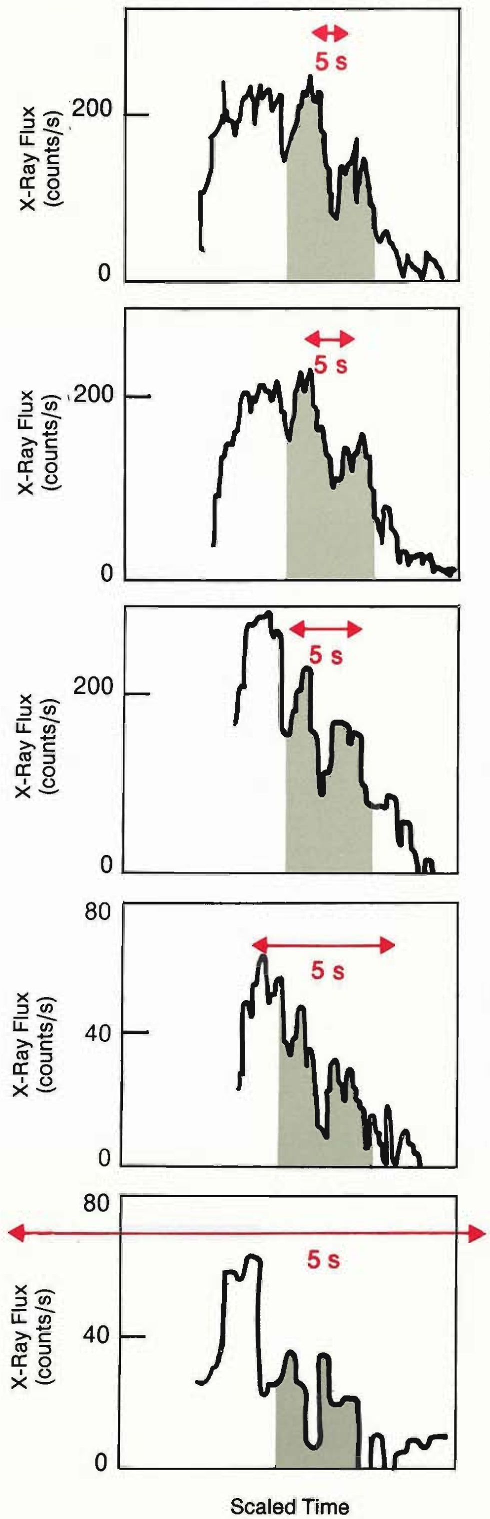


Fig. 15. Observed x-ray intensity curves for Type II bursts. Each of these curves has been normalized to the characteristic time for the rising and falling structure in the decay (note the 5-second indicator in each curve), showing the similarity of the oscillations during the decay. Such time histories 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

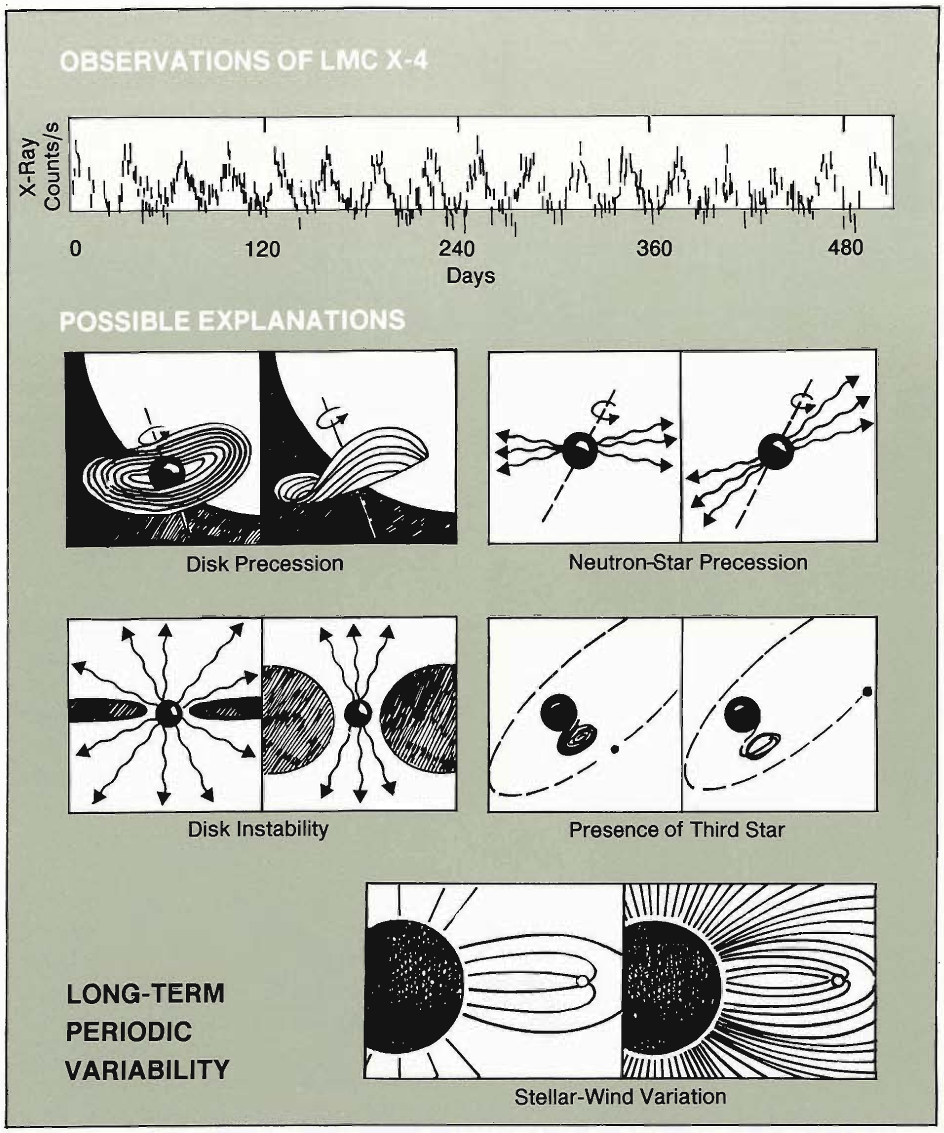


Fig. 16. The observed periodic long-term variation of the flux of LMC X-4 (top) and possible causes of such variation in this and other x-ray binaries. These causes include precession of a tilted disk, precession of the neutron star itself, a disk instability that periodically blocks part of the x rays, 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 precessing 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 precessing 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.

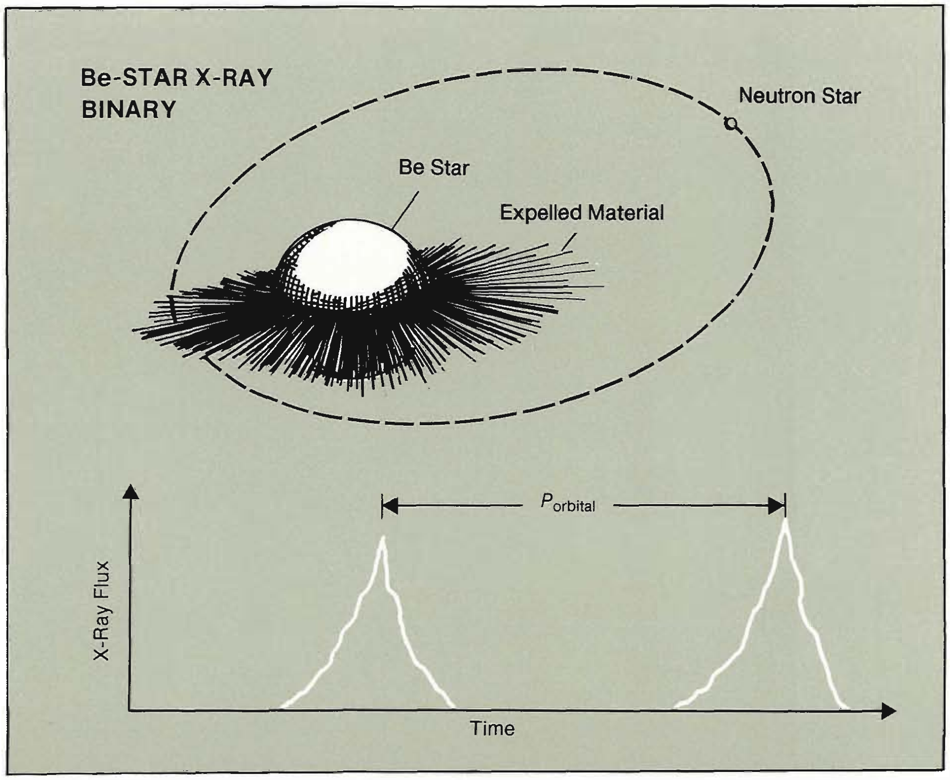


Fig. 17. An x-ray binary system consisting of a young, hot Be star and a neutron star in eccentric orbit may show periodic x-ray flares that occur once an orbit when the neutron star is closest to the Be star and its equatorial wind or disk of expelled material. ◀

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 varies 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 10^{12} 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 nonthermal 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 synchrotron 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.

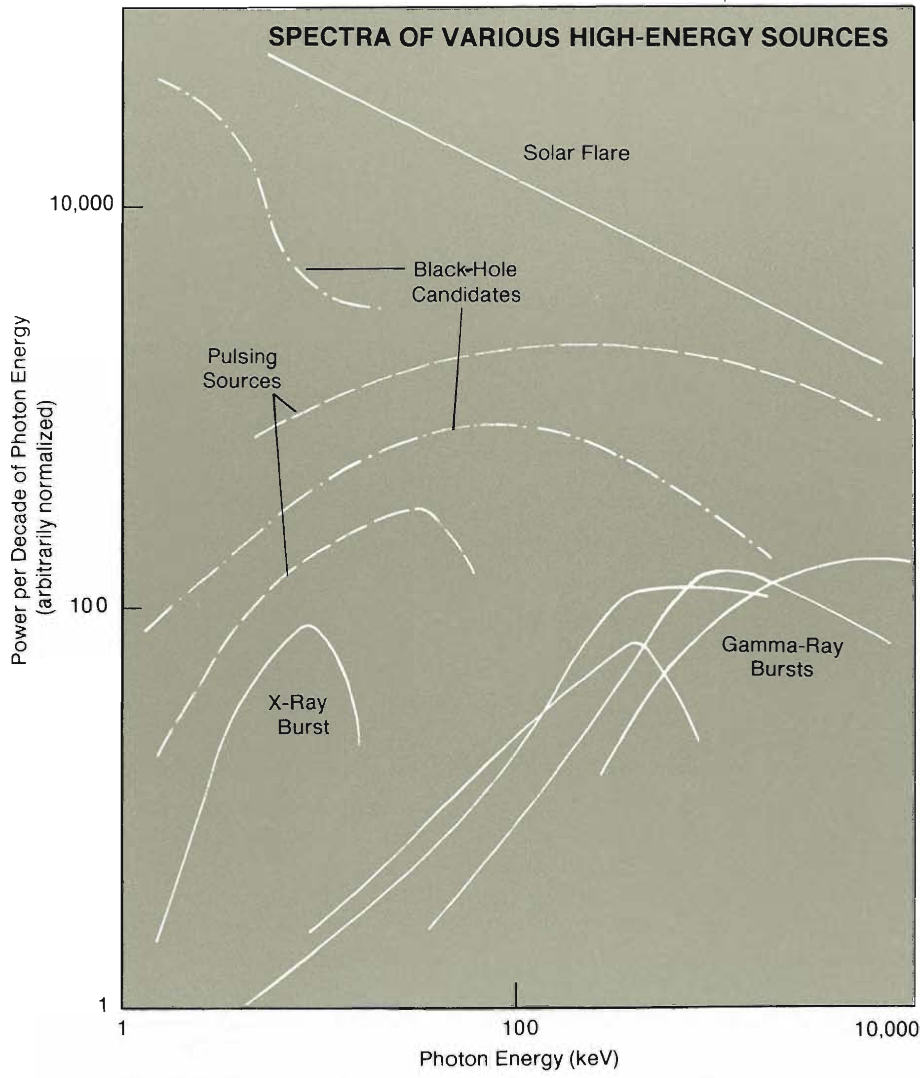
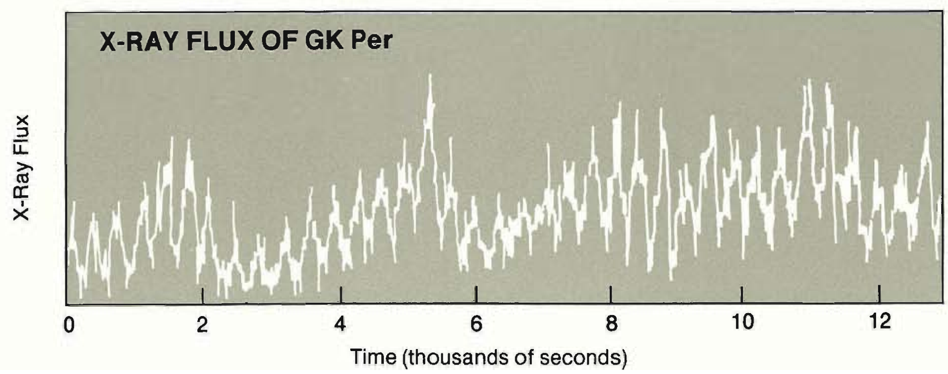


Fig. 18. Spectra of various high-energy sources showing the relative deficiency of x rays in gamma-ray bursts. The spectra of the black-hole candidates are those of LMC X-1 when its spectrum is softest (upper curve) and of Cyg X-1 when its spectrum is hardest (lower curve). The solar flare is one that 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 10^7 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.

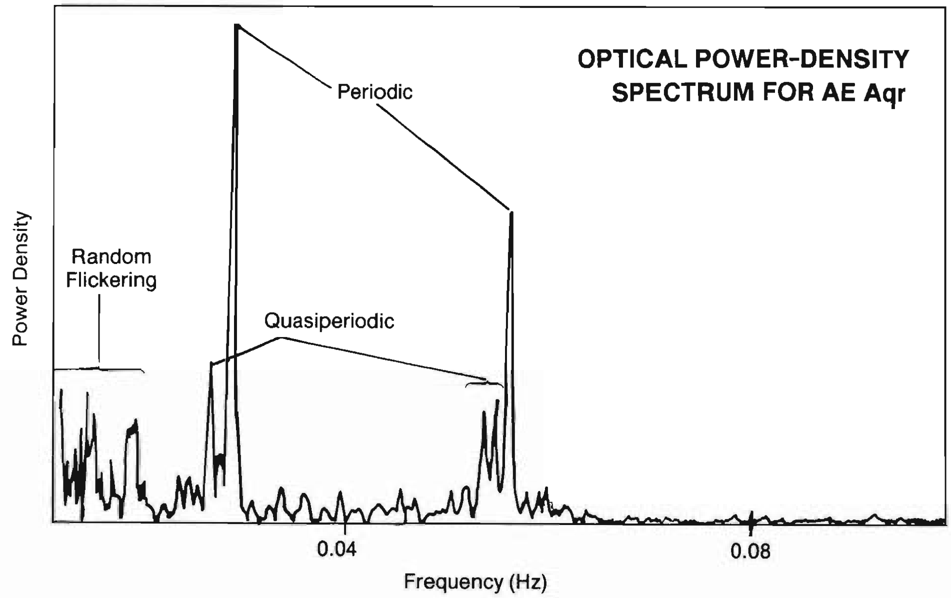
Strongly magnetic degenerate dwarfs are the analogues of accretion-powered pulsars: rotation of the degenerate-dwarf star causes the radiation to sweep periodically across the observer. One example is the cataclysmic variable GK Per, observed by EXOSAT during a large brightening. It has an x-ray flux 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 "Quasiperiodic 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).

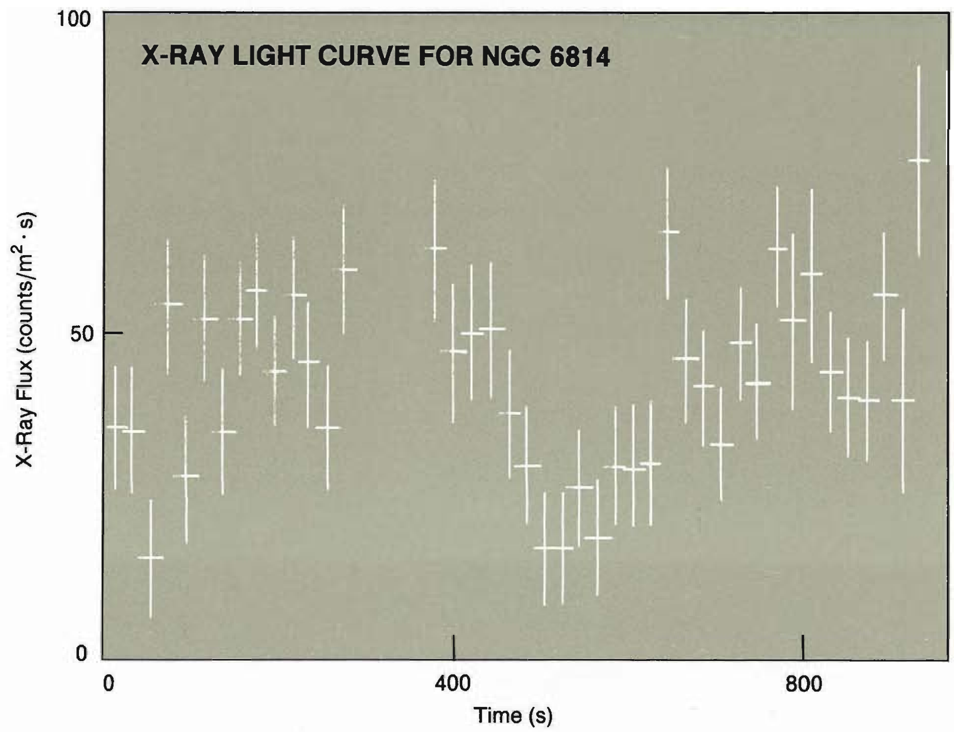
Currently, Cygnus X-1 and A0620−00 are the only strong black-hole candidates in our galaxy; GX0339−4 is a more questionable one. The best candidate for a black hole at present is LMC X-3, a source in the Large Magellanic Cloud.

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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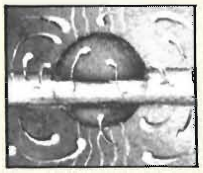


New Analysis Techniques

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.

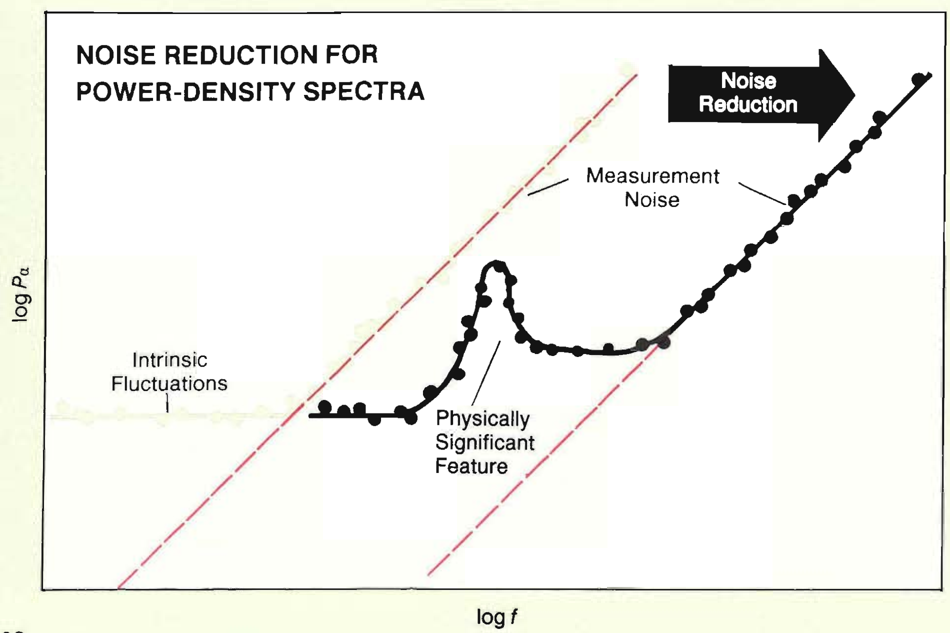
The large-area x-ray detectors on the next generation of satellites will provide very high counting rates (20,000 counts per second from bright sources) and make possible microsecond time resolution. This will greatly reduce fluctuations in the measured pulse shape caused by photon statistics and the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

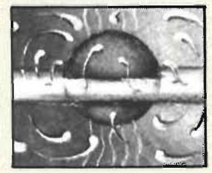
As the precision of pulse-arrival times is increased—by enlarging the detector area and filtering the pulse waveform—arrival-time variations caused by fluctuations in the rotation rate of the neutron star become more apparent (figure). These spin-rate fluctuations can then be studied better, providing 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 $P_a(f)$, 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 4×10^{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 2.4×10^{14} grams per cubic centimeter—a little 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 core. In this case the vortices are 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

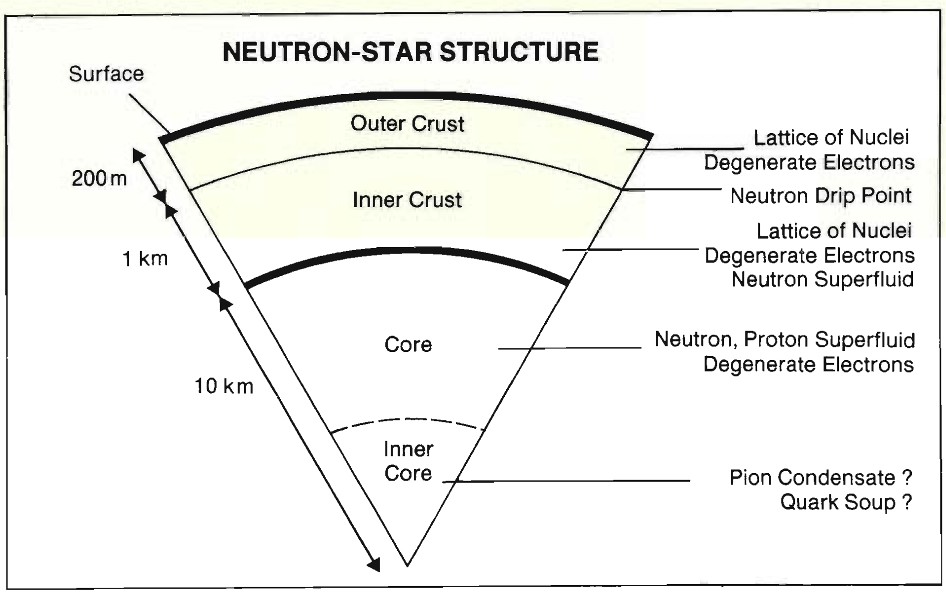


Fig. 1. The outer crust of a neutron star consists of a solid lattice of nuclei embedded in a sea of relativistic degenerate electrons. The surface of the crust may be solid or liquid, depending on the temperature and the strength of the surface magnetic field. The inner crust is a solid lattice of nuclei 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. ▶

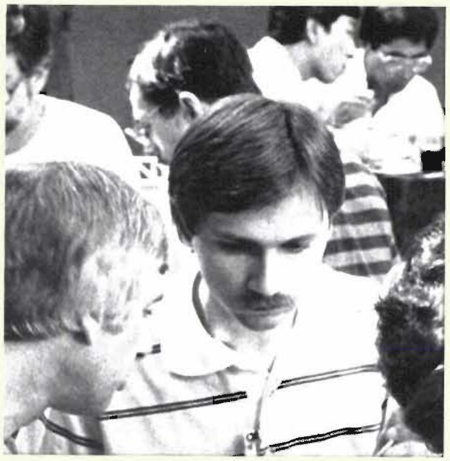
that the neutron superfluid in the core is only *weakly* coupled to the rest of the star, taking days to years to respond to changes in the rotation rate of the crust. To the extent that this is true, a neutron star can be idealized as consisting of just two components: the crust plus electron and proton 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

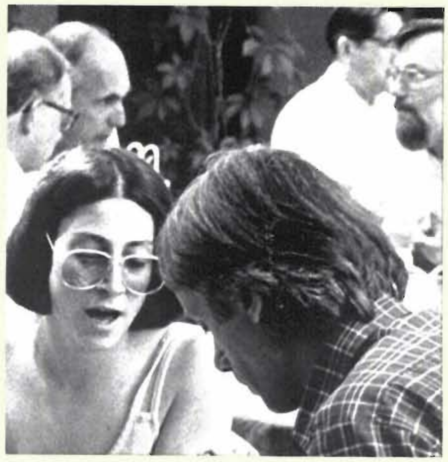
For a decade, the model used to explain



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 macroglitches 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 proc-



ess, 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 ($\alpha = 0$) 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

THEORETICAL POWER-TRANSFER FUNCTIONS

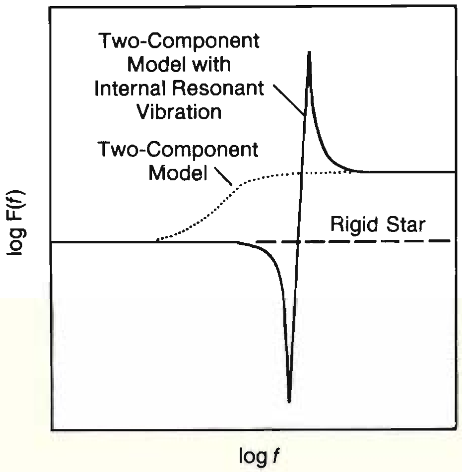
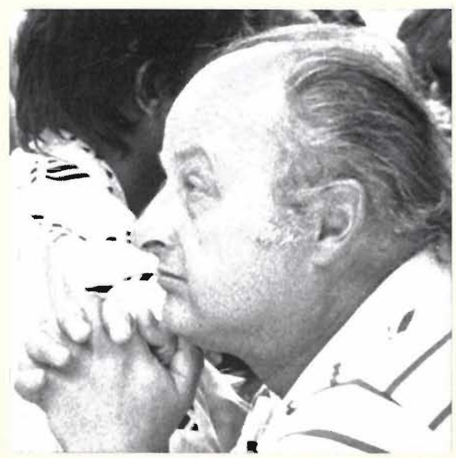


Fig. 2. Logarithmic plots of theoretical power-transfer functions F(f) for three distinct neutron-star models: a rigid star (dashed line), a two-component model (dotted line), and a two-component model in which the vortex array in the superfluid neutron core can be set vibrating (solid line). The shape 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.



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.

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 expected to rotate by forming arrays of vortices, whereas the proton superfluid in the core is expected 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 effectively, 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 $400P$ 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 are 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.

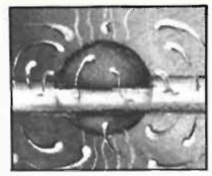
What then is the explanation of the macroglitches and the long post-glitch relaxation, which first suggested the idea of weak coupling between the crust and the

core of neutron stars? One possibility builds on the fact that the neutron vortices in the inner crust are expected to be 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 accretion-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 currently, 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 we 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-1). 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.

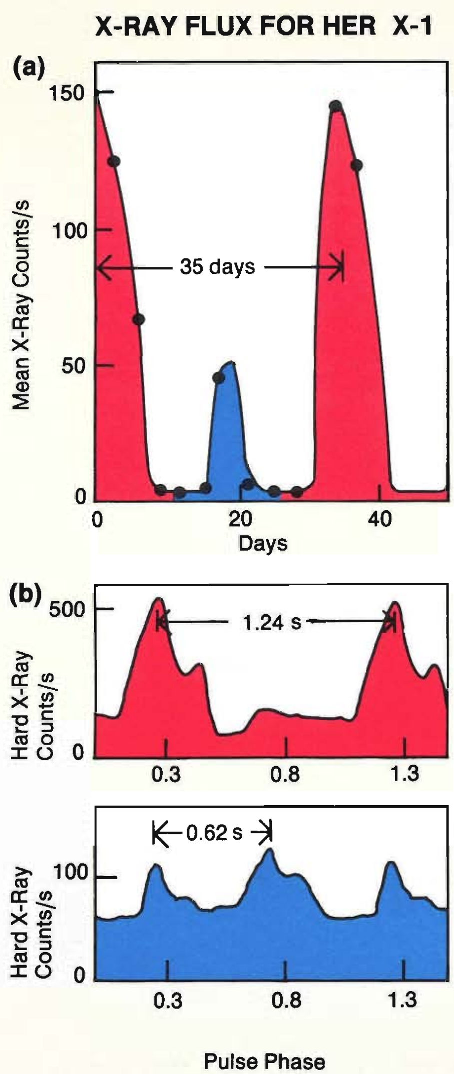
The most interesting cycle is the 35-day one. The source follows a slightly irregular pattern in which it is bright for about 9 days and then relatively dim for about 26 days (figure). For years the most popular explanation for this 35-day cycle has been periodic obscuration by a tilted, twisted, and precessing accretion disk. However, the *cause* of the tilt and precession has not been well understood. One popular explanation, that the companion star is precessing (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.

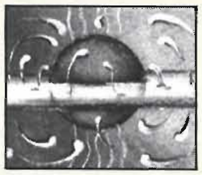
New studies by the EXOSAT satellite, reported at the Taos workshop, strongly support an alternative suggestion. In this study Her X-1 was monitored for hundreds of hours and approximately thirty times more x rays were recorded than in all previous studies put together. As a result, the pulse shape and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





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 precessing has major implications for two key aspects of neutron-star structure. First, it would imply that the superfluid 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 interior of a 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-1). 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 corotation 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 are 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. 1b). 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.

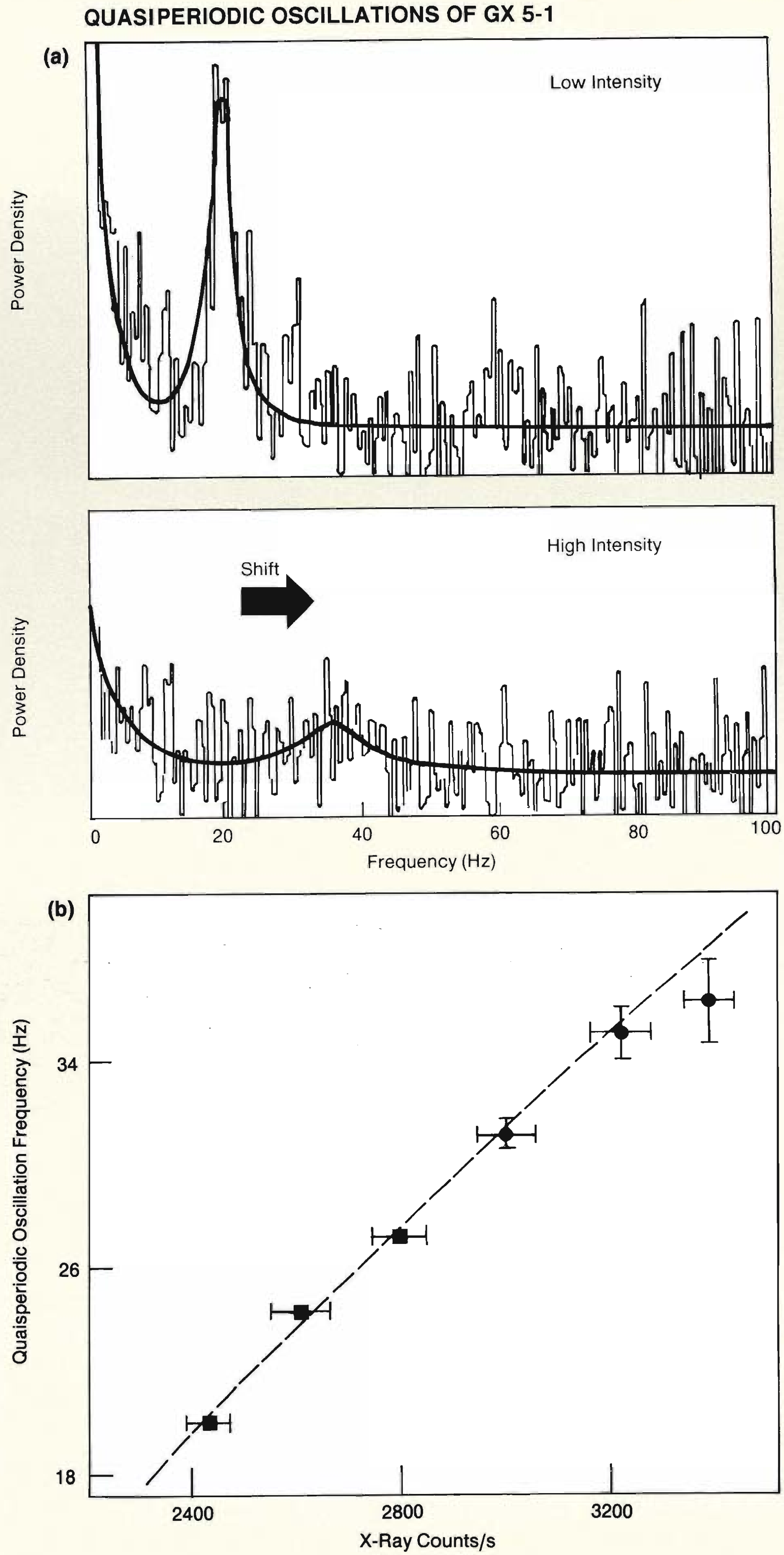


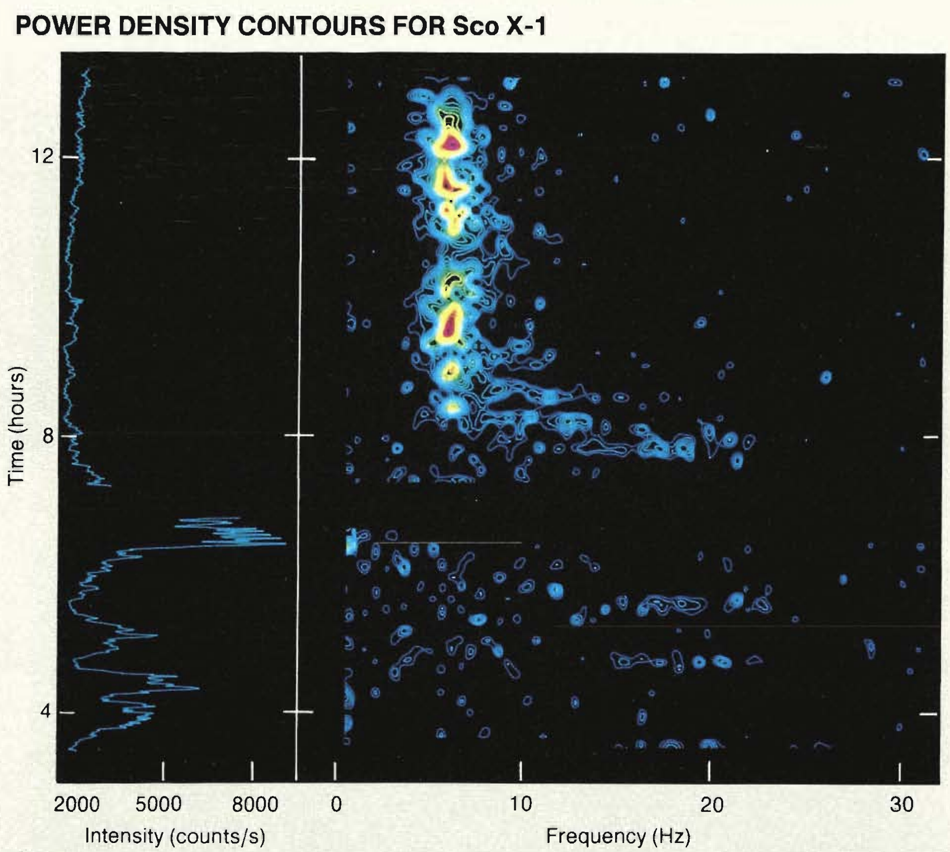
Fig. 1. (a) The quasiperiodic oscillations of GX 5-1 are seen as a broad peak in averaged power-density spectra that shifts from 20 to 36 Hz as the intensity of the source increases. (b) A strong positive correlation exists between the centroid frequency of the quasiperiodic oscillations and source intensity. 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.▼



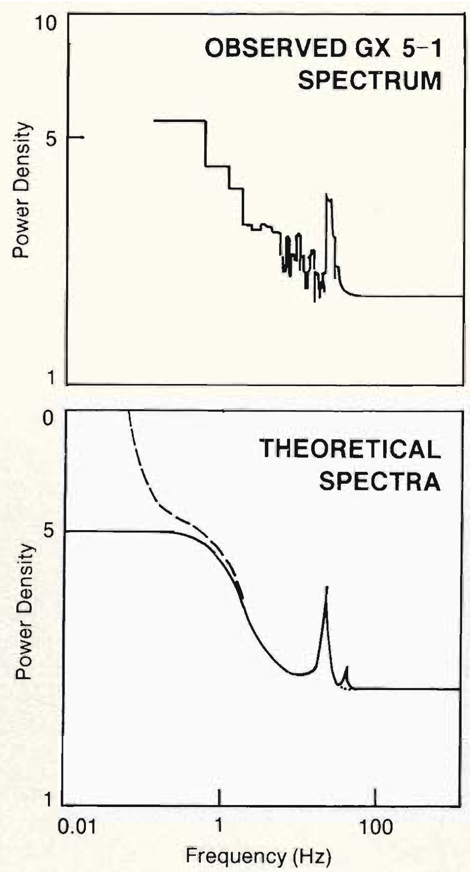


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Fig. 3. An observed power-density spectrum for GX 5-1 (top panel) compared to two theoretical power-density spectra (bottom panel) calculated for the beat-frequency model using different parameter values. Because the low-frequency behavior of the two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

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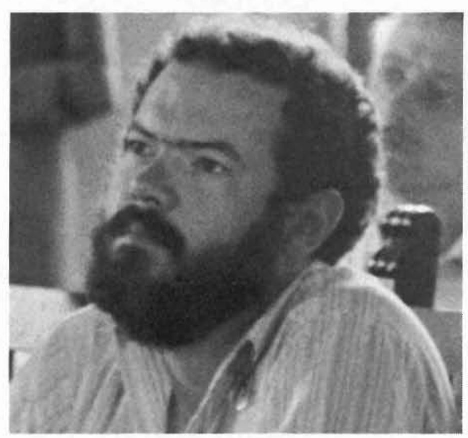

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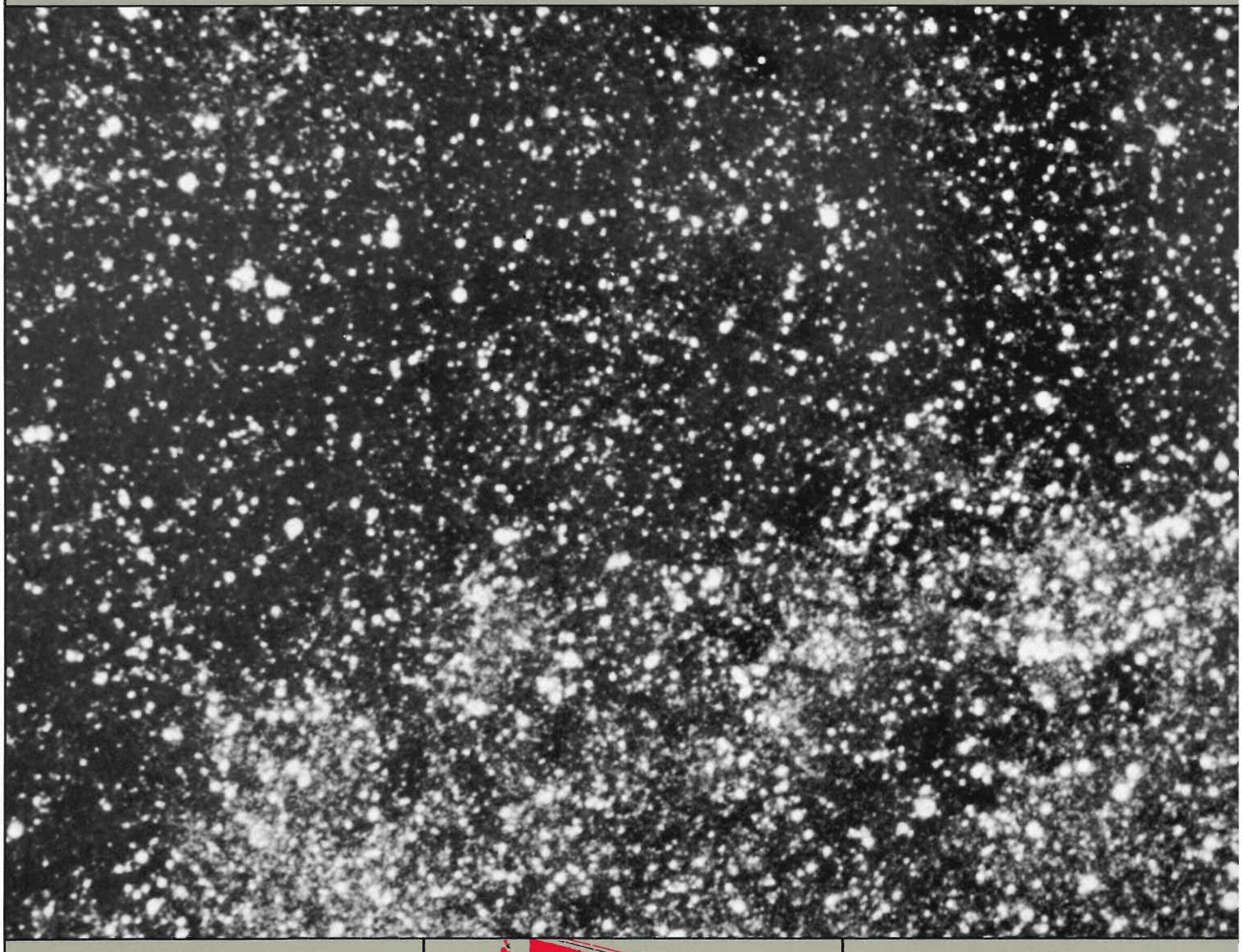
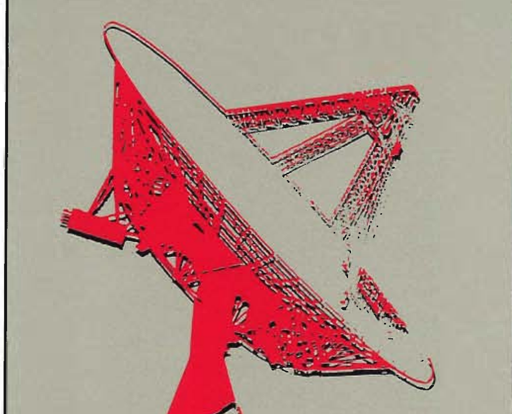
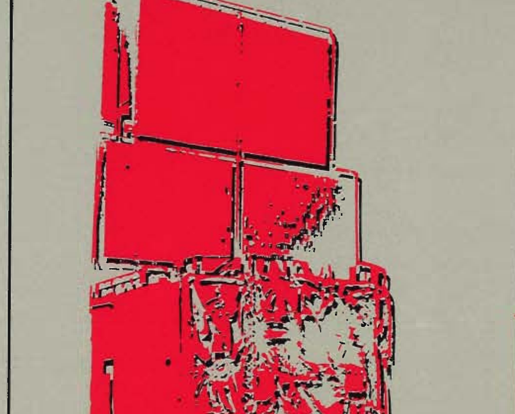


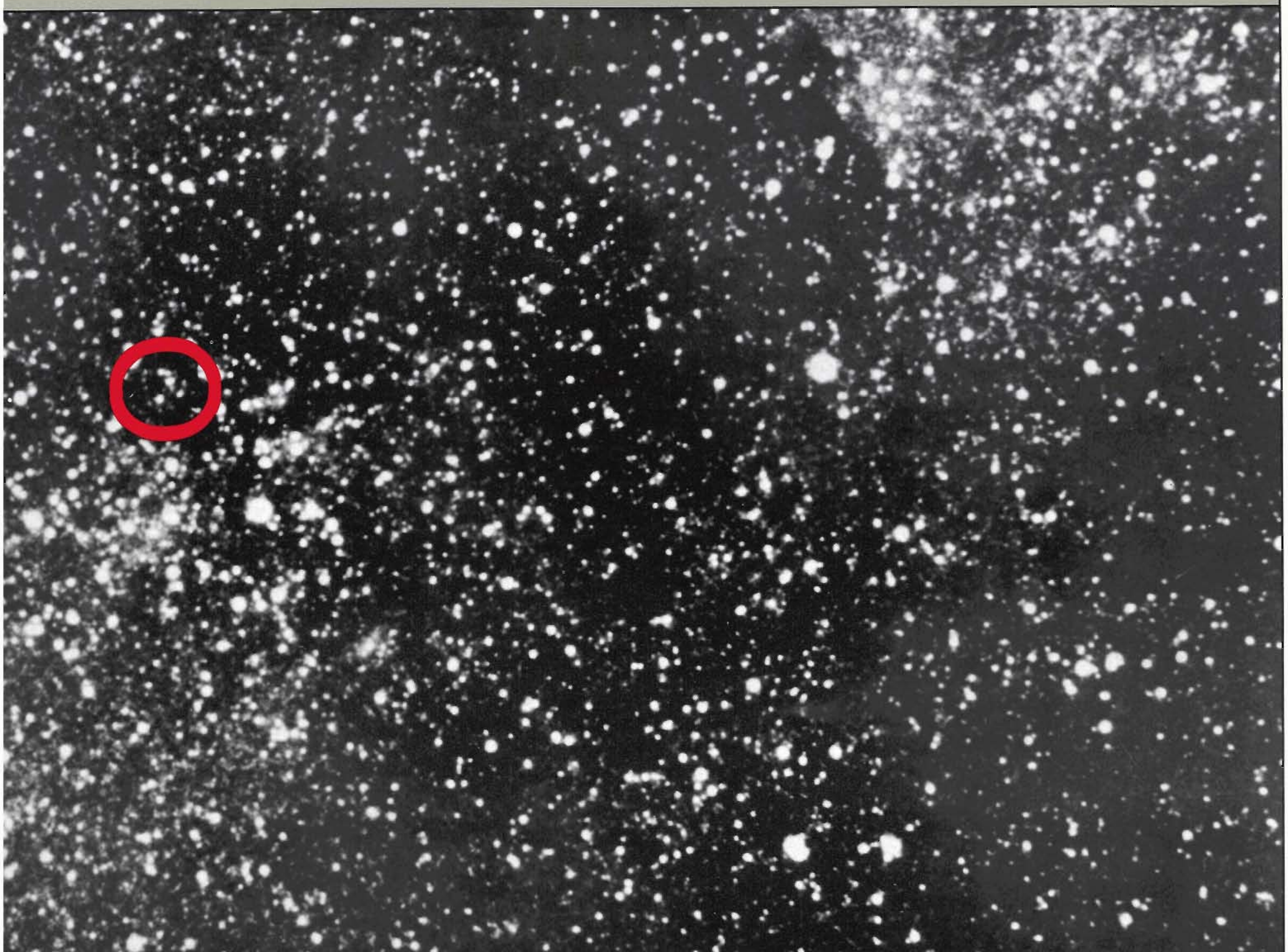
Photo by Dennis di Cicco

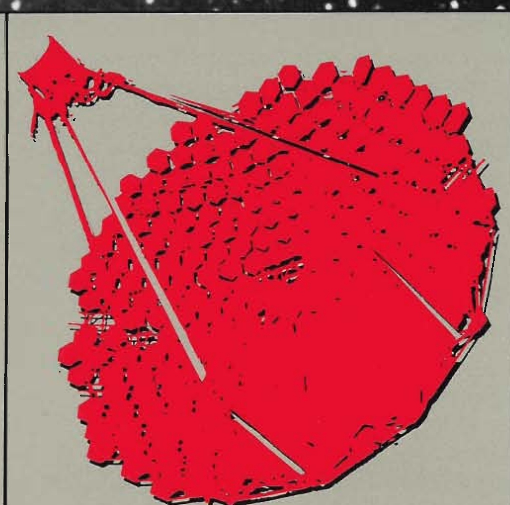




CYGNUS X-3

And The Case For Simultaneous Multifrequency Observations





by France Anne-Dominic Córdova

Although the visible radiation of Cygnus X-3 is absorbed in a dusty spiral arm of our galaxy, its radiation in other spectral regions is observed to be extraordinary. In a recent effort to better understand the causes of that radiation, a group of astrophysicists, including the author, carried

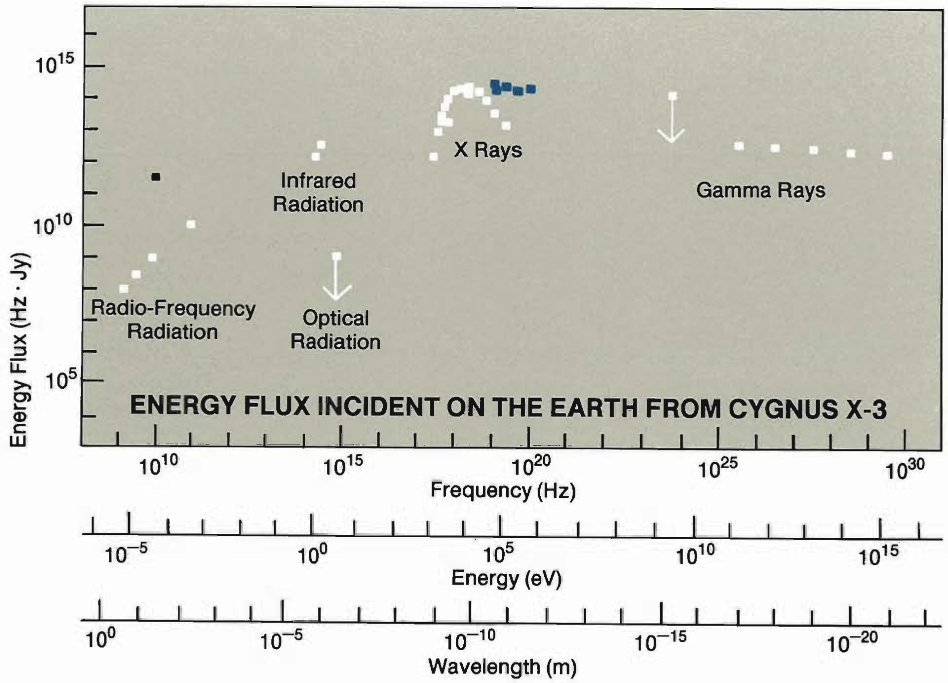


Fig. 1. The energy flux at the earth due to electromagnetic radiation from Cygnus X-3 as a function of the frequency and, equivalently, energy and wavelength of the radiation. The data points in white are typical values for this variable source during quiet states, those in gray are values obtained during a period of apparently increased x-ray activity, and the point in black is the maximum flux observed during the first radio-frequency activity of the source to be detected. As indicated by the arrows, the fluxes due to optical radiation and to gamma rays with energies of about 10^9 eV are upper limits. (The energy flux is expressed in hertz times janskys (Jy), where 1 jansky = 10^{-26} watt · meter^{-2} · hertz^{-1}.)

out an unprecedented experiment. For two days in October 1985 they directed toward the source a variety of instruments, located in the United States, Europe, and space, hoping to observe, for the first time simultaneously, its emissions at frequencies ranging from 10^9 to 10^{18} hertz. The battery of detectors included a very-long-baseline interferometer consisting of six radio telescopes scattered across the United States and Europe; the National Radio Astronomy Observatory's Very Large Array in New Mexico; Caltech's millimeter-wavelength interferometer at the Owens Valley Radio Observatory in California; NASA's 3-meter infrared telescope on Mauna Kea in Hawaii; and the x-ray monitor aboard the European Space Agency's EXOSAT, a satellite in a highly elliptical, nearly polar orbit, whose apogee is halfway between the earth and the moon. In addition, gamma-ray detectors on Mount Hopkins in Arizona, on the rim of Haleakala Crater in Hawaii, and near Leeds, England, covered frequencies above 10^{25} hertz within a few days. (The experiment is represented schematically in the opening figure.)

Although not the first attempt at simultaneous multifrequency observations, the October experiment was special in two respects: it covered a wider range of frequencies than any previous effort, and its focus was an object that has tentatively been identified as a source of extremely energetic gamma rays and thus of extremely energetic particles. It had previously been thought unlikely that particles could be accelerated to extreme energies in stars; rather, the acceleration was thought to be the result of events in interstellar space, such as the passage through an interstellar cloud of a shock wave from a supernova explosion. The possibility that particles could be accelerated in Cygnus X-3 to energies greater than those attained at the most powerful of today's accelerators has attracted the attention not only of astrophysicists but also of particle physicists.

The current, but incomplete, understanding of Cygnus X-3 has been pieced together from studies of its emissions in widely different spectral regions. Observation of the universe at frequencies other than optical began with the development of radio telescopes in the 1950s and broadened with the advent of x-ray telescopes in the late 1960s. These instruments revealed the existence of previously unknown sources, and an immediate need arose for information about the intensity, energy, and temporal variation of their optical radiation. But acquiring such information required many hours of observing time, hours that were not easy to come by at the dedicated and relatively few optical telescopes of the time.

This difficulty was addressed by the establishment of national astronomical facilities accessible to scientists from any institution. These facilities, which include satellite- and ground-based instruments, have benefited the fields of astronomy and astrophysics enormously. The accompanying insert describes briefly those available today.

Access to the national astronomical facilities helped solve one problem, but another soon became obvious. The radiation from most astronomical sources, particularly high-energy sources, varies temporally, often rapidly and unpredictably. A complete picture of a variable source requires *simultaneous* multifrequency observations. In the past few years groups of astronomers, some including as many as thirty participants from as many as twenty institutions, have attempted such observations. As a testament to their importance, the European Space Agency devotes at least 60 percent of the EXOSAT agenda to experiments coordinated with observations at other frequency ranges. Among the most successful attempts at simultaneous observations have been those aimed at flare stars, active galaxies, sources of x-ray bursts and transients, and novas.

Today's understanding of Cygnus X-3 is an excellent example of the power of multifrequency, although not simultaneous, observations; the gaps in that understanding are ample evidence of the need for simultaneous coverage and for better methods of achieving it. I will review what has been learned about the radiation emitted by this source, first from non-simultaneous experiments and then from previous attempts at simultaneity, and what has been hypothesized about the origins of those emissions. Current information about the energy incident upon the earth from the source is displayed for reference in Fig. 1.

One View at a Time

Cygnus X-3 first entered the catalogue of known astronomical objects in 1966 as but one of the bright x-ray sources discovered in that decade. It has since provided astrophysicists with considerable intellectual excitement.

National Astronomical Facilities

Among the first of the national astronomical facilities was Kitt Peak National Observatory near Tucson, Arizona. Its 4-meter Mayall telescope, the third largest optical telescope in the United States, was opened to guest observers in 1973, and many x-ray astronomers, in particular, soon began to study for themselves the optical counterparts of x-ray sources. Kitt Peak National Observatory, which today provides six other optical telescopes, Cerro Tololo Inter-American Observatory in northern Chile, which offers a view of the southern sky through a twin of Kitt Peak's Mayall telescope, and the National Solar Observatory, which includes solar telescopes on Kitt Peak and Sacramento Peak in New Mexico, compose the National Optical Astronomy Observatories. NOAO is operated for the National Science Foundation by AURA, the Association of Universities for Research in Astronomy. Sixty percent of the time available on the NOAO telescopes is allocated to guest observers on the merit of their proposed research.

The most widely used guest facility is one located in space—an ultraviolet telescope aboard the International Ultraviolet Explorer satellite launched by NASA in 1978 and still operating today. The telescope, a collaborative effort by NASA, the European Space Agency, and the United Kingdom's Science and Engineering Research Council, has been used to study almost every known type of astronomical source.

In 1978 NASA also launched Einstein, the second of its High Energy Astrophysical Observatory satellites and the first to carry a focusing x-ray telescope. This facility caused the migration of astronomers to take a new turn as optical astronomers studied the x rays emitted by stars that radiate primarily in the visible region. Einstein became inoperative in 1981; its role as a guest x-ray facility is filled today by the European Space Agency's EXOSAT satellite launched in 1983.

In 1979 NASA's Infrared Telescope Facility on 13,800-foot Mauna Kea, far above much of the earth's infrared-absorbing water vapor, welcomed guest observers to another region of the spectrum. And in 1981 the Very Large Array of twenty-seven radio telescopes at the National Radio Astronomy Observatory near Socorro, New Mexico, provided observers with high-resolution images of radio-frequency sources.

Scientists from Los Alamos National Laboratory's Space Astronomy and Astrophysics Group have used all of these facilities in their explorations of accreting compact stars in binary systems and of pulsing, collapsed remnants of supernovas.

The techniques for collecting and analyzing astronomical data differ dramatically from one spectral region to another, but the national facilities offer how-to assistance and computer software in addition to observing time. Such user-friendliness encourages astronomers to venture outside a narrow specialty and explore many spectral regions, each containing different but complementary information about the physics of a source. ■

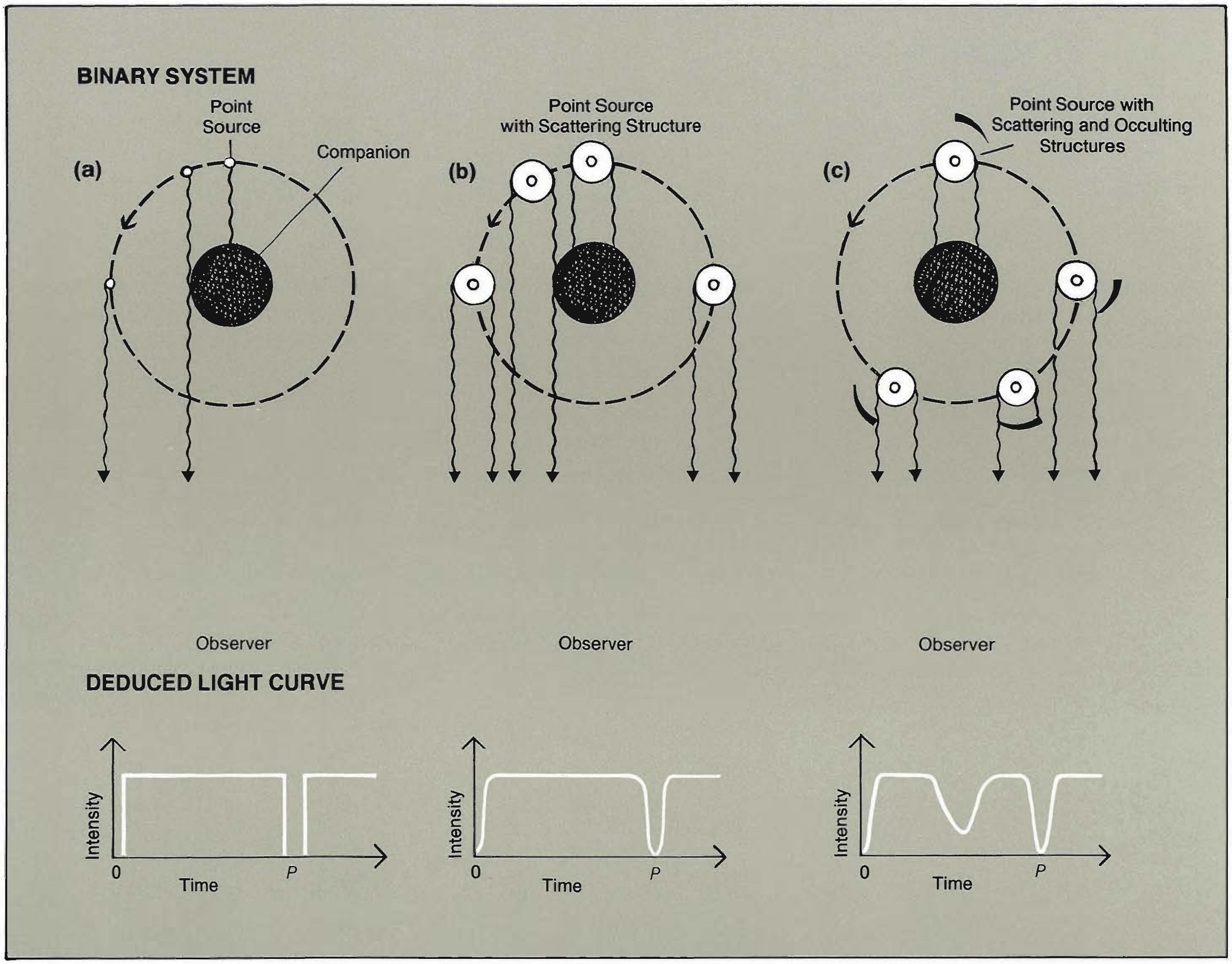


Fig. 2. Modulation by orbital motion of the intensity of radiation from a binary system. (a) Consider a binary system consisting of a pointlike, nonvariable source of radiation and a larger, nonradiating, opaque, spherical companion rotating about each other in a circular orbit. (The system is shown in cross section through the orbital plane.) The intensity of the radiation from the system, observed at a far distance along a line of sight perpendicular to the axis of rotation, undergoes an abrupt decrease to zero intensity once per orbital period as the source is eclipsed by the companion. In the light curve for the system (graph of intensity versus time during an orbital period), the decrease appears as a negative square pulse lasting for a fraction of the period P equal to the angle in radians subtended by the companion at the source. (In all the light curves shown $t = 0$ corresponds to the position of the source directly behind the companion star.) (b) Suppose that the system includes in addition a structure whose extent above and below the plane of the orbit is azimuthally symmetric about the source. If this structure is composed of matter that scatters the radiation, the source appears extended, and the periodic decreases in intensity are gradual with a width at half-minimum approximately equal to that in (a). If, as illustrated, the radius of the scattering structure is less than that of the companion, the minimum intensity is zero. However, if the radius of the structure is greater than that of the companion (or if the axis of rotation of the binary and the line of sight are not perpendicular), the minimum intensity is nonzero. (c) Suppose further that the system includes a structure whose extent above and below the plane of the orbit is azimuthally asymmetric about the source. If this structure is opaque to the radiation, then an additional periodic decrease in intensity is observed. The azimuthally asymmetric variation in height of the opaque structure results in a modulation that is asymmetric about the minimum; the phase of the minimum (relative to the minimum due to the scattering structure) depends on the location of the opaque structure. The light curve sketched corresponds to an opaque structure located on an arc of a circle centered on the source; the height of the structure varies linearly from some maximum at its leading edge to zero at its trailing edge. The structures in (b) and (c), although seemingly contrived, are simplified versions of structures invoked to explain the x-ray light curves of x-ray binaries in which the point source is a compact star (such as a neutron star) and the companion is a more or less normal, low-mass star. The scattering structure exemplifies an optically thick corona within an accretion disk (see Fig. 3), and the opaque structure exemplifies a bulge on the outer edge of the accretion disk.

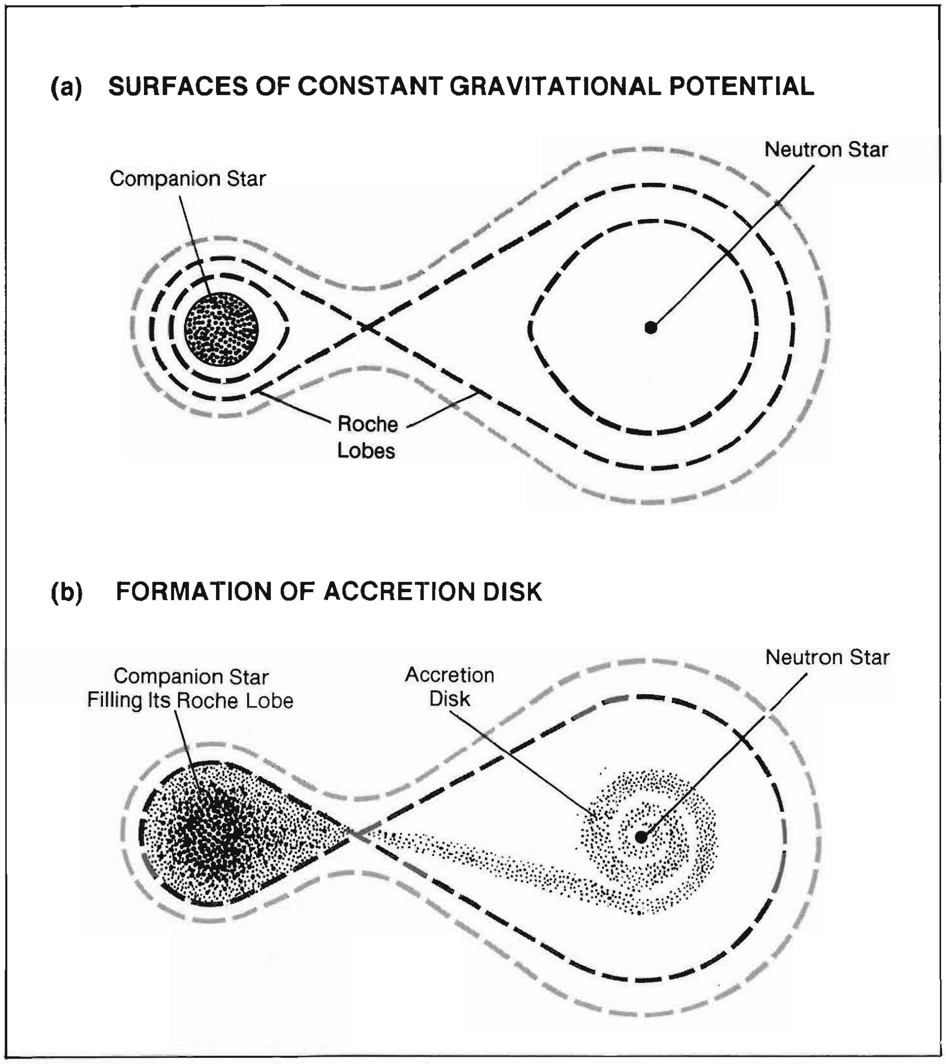


Fig. 3. The gravitational potential in the vicinity of a binary system can be visualized by means of surfaces on which the gravitational potential is constant. Shown in (a) are cross sections (through the orbital plane) of three such equipotential surfaces for a binary system composed of a neutron star and a low-mass companion star. Note the change in topography of the equipotential surfaces, as the gravitational attraction decreases, from two disconnected surfaces, one surrounding each star, to a single connected surface surrounding both stars. Of particular interest is the surface consisting of two so-called Roche lobes with a single point in common, for this is the smallest equipotential surface providing an energetically easy path for transfer of matter from one star to the other. In (a) the companion star is smaller than its Roche lobe, but during the course of its stellar evolution, it may expand and fill its Roche lobe, as shown in (b). Then matter from the companion star can move through the connecting point to the Roche lobe of the neutron star and be captured in its gravitational field. The result is an accretion disk, coplanar with the orbital plane, from which matter gradually spirals toward the surface of the neutron star, losing angular momentum and gravitational potential energy and gaining kinetic energy. Interactions of this energetic matter with the neutron star or with other matter in its vicinity produce x rays.

X Rays. The field of x-ray astronomy was launched in the early sixties when a series of rockets carried gas-filled proportional counters with thin plastic windows a hundred miles above the earth. (X rays and ultraviolet light are the forms of electromagnetic radiation most highly absorbed by the earth's atmosphere.) Some of the galactic x-ray sources first discovered exhibited periodic, abrupt, and total decreases in x-ray intensity. Such an intensity modulation is consistent with occultation of a point source of x rays by a larger object as they orbit about each other (Fig. 2). Astronomers therefore identified these sources as binary systems and proposed an accretion model as an explanation for the x rays. That is, matter is being transferred from a more or less normal companion star to a compact star (a white dwarf, a neutron star, or a black hole), and, as it falls toward the surface of that star, its gravitational potential energy is converted into kinetic energy. Interactions of this energetic matter with other matter in the vicinity of the compact star produce the x rays. If the companion star has a low mass (equal to or less than about $M_{\odot}$, the mass of the sun) and fills its Roche lobe, the accreting matter forms a disk around the compact star and, losing angular momentum through some viscous process, gradually spirals toward the surface (Fig. 3). If the companion star is more massive, matter accretes directly onto the compact star from a stellar wind leaving the companion star.

Data gathered in the early seventies by the Uhuru and Copernicus satellites revealed a 4.8-hour periodicity (more exactly, a 4.79-hour periodicity) in the x-ray intensity of Cygnus X-3. The period is now known to be slowly lengthening. Interpretation of this periodicity as modulation by orbital motion of a binary system was natural, although two of its features caused some doubt. The period was shorter, by a factor of 10, than the orbital period of any other x-ray binary then known, and the modulation was quasi-sinsuoidal and asymmetric about a minimum intensity equal to about 40 percent of the maximum (Fig. 4). Today, other x-ray binaries with comparably short orbital periods and similar orbital modulations are known, and, despite lack of conclusive evidence, most astrophysicists are confident that Cygnus X-3 is a binary system. If so, it is an extremely close binary system. Kepler's third law, together with the orbital period and reasonable estimates for the component masses, tells us that the two stars can be no farther apart than about $2R_{\odot}$, where $R_{\odot}$ is the radius of the sun.

Data about the x rays from Cygnus X-3 have been collected over an energy range

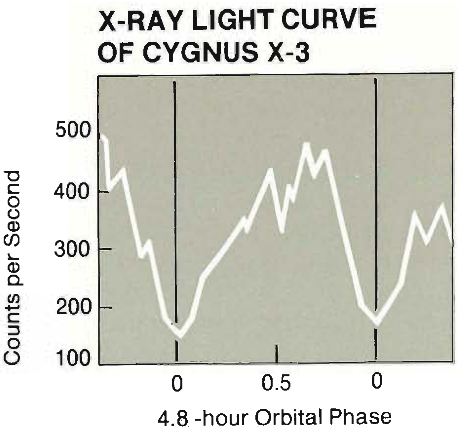


Fig. 4. This sketch of the x-ray light curve of Cygnus X-3 is based on EXOSAT data taken in September 1984 by the author, K. O. Mason, and N. E. White. Note the broad dip to the minimum intensity, the asymmetry of the dip about the minimum, and the large and rapid variations in intensity outside the dip.

from 1 to 150 keV during numerous balloon- and satellite-mounted experiments (1 keV = 1000 electron volts $\cong$ 2.4 $\times$ 10^{17} hertz). The observed x-ray spectrum shows a sharp decrease in flux at energies below a few keV (see Fig. 1). This cutoff is attributed to absorption by interstellar gas and possibly by a medium local to the source. EXOSAT data show that the intensity of x rays with energies between 6 and 30 keV is less modulated by orbital motion than that of x rays with energies between 3 and 6 keV and that the intensity ratio of the harder to the softer x rays increases at the x-ray minimum. These observations must be accounted for in any model of the source.

The x-ray intensity of Cygnus X-3 shows intrinsic temporal variations as well as the 4.8-hour orbital variation. On short time scales (50 to 1500 seconds) the intensity of the softer x rays sometimes undergoes quasiperiodic oscillations. On longer time scales (weeks to months) the average intensity level varies randomly, by a factor of 10 or more, between low and high states.

The inherent x-ray luminosity of Cygnus X-3, which can be calculated from its observed x-ray spectrum and its estimated distance from the earth (about which more below), varies from about 10^{37} to 10^{38} ergs per second. (For comparison, the sun's total luminosity is 4×10^{33} ergs per second.) Such a high x-ray luminosity, together with the high luminosities of the source in other spectral regions, makes it unlikely that the compact star in the system is a white dwarf. If the compact star is a neutron star, as seems likely, and if the mass of that neutron star is similar to the measured masses of other neutron stars (about $1.4M_\odot$), then the x-ray luminosity of Cygnus X-3 is very close to the Eddington limit. This limit, which equals $(M/M_\odot) \times 10^{38}$ ergs per second for a star of mass M, is the radiation rate beyond which the outward radiation force on accreting matter is greater than the inward gravitational force.

A satisfactory model has recently been developed for an x-ray binary with an orbital modulation similar to that of Cygnus X-3 (see "X1822−371 and the Accretion-Disk Corona Model"). According to that model the x rays originate from a point source, but the source appears extended because the x rays are scattered into the line of sight by an extensive corona of ionized matter surrounding the point source (see Fig. 2). Such a corona could be formed in an accretion disk by the radiation pressure of a compact star radiating near the Eddington limit. The existence of a corona in Cygnus X-3 could explain why it is difficult to determine whether the system contains a neutron star. A sure signature of a neutron star, and one that has served to identify neutron stars as components of many other x-ray binaries, is a rapid pulsation in x-ray intensity. The pulsation results when matter accretes onto a rotating, magnetized neutron star (a pulsar) whose rotation and magnetic axes are not aligned. Then accretion occurs preferentially on the magnetic poles of the neutron star, creating a beamlike pattern of x rays that swings into and out of the line of sight with the rotation period of the neutron star. If Cygnus X-3 contains a pulsar surrounded by a corona, the corona could scatter the x rays so much that this lighthouse effect is destroyed.

Radio-Frequency Radiation. Following the discovery of Cygnus X-3 as an x-ray source, its radio-frequency counterpart was identified and monitored sporadically. Although the brightest of the known radio counterparts of galactic point x-ray sources, it was nevertheless a very weak radio source. Then, on 2 September 1972 a Canadian radio astronomer by chance ob-

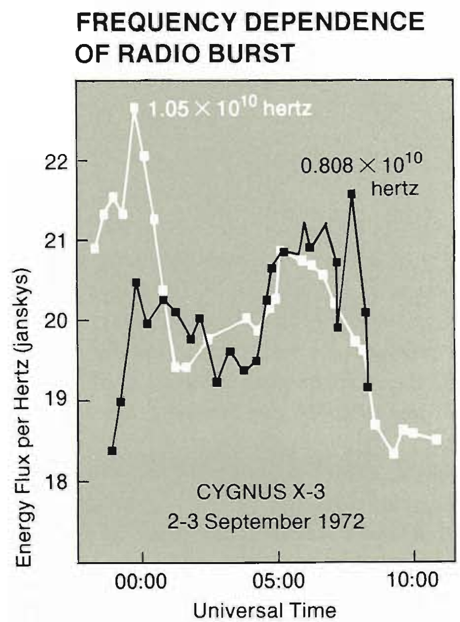


Fig. 5. The initial stages of the first detected radio-frequency burst from Cygnus X-3 were observed at two frequencies. Note that the maximum energy flux per hertz attained is greater at the higher frequency, and that the maximum at the lower frequency occurred later in time. These features have been found to be characteristic of the radio-frequency bursts and are suggestive of a possible mechanism (see text). (Figure adapted from R. M. Hjellming, **Science** ***182(1973):1089.)***

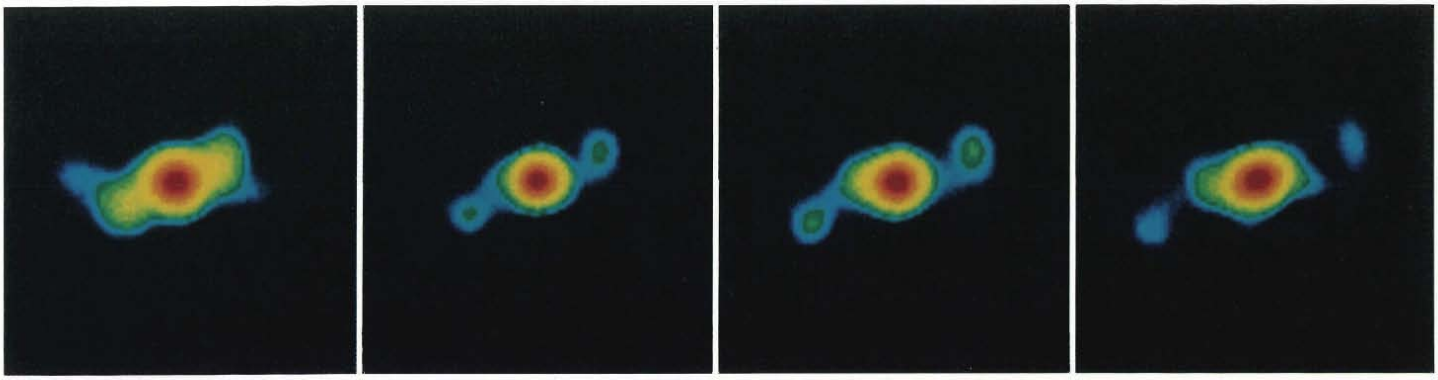


Fig. 6. A chronological sequence of color-coded radio-frequency intensity maps of the binary system SS 433 obtained with the VLA during the first four months of 1981. The low-intensity (blue) regions moving outward from the source are interpreted as synchrotron radiation emitted by relativistic electrons that have been injected into opposing jets of plasma emanating from the source. The speed of the jets is about one-fourth the speed of light, which is comparable to that of the jets emanating from Cygnus X-3. The existence of opposing jets in SS 433 and Cygnus X-3 and the high total luminosities of the systems indicate that these stellar objects may be small-scale versions of active galactic nuclei and quasars. (The images, made by R. M. Hjellming and K. J. Johnston, are the property of the National Radio Astronomy Observatory.)

served that the radio intensity of the source was a hundred times greater than usual and increasing. Radio astronomers all over the world immediately began to monitor the source at frequencies ranging from about 10^9 to 10^{11} hertz. (Other astronomers, too, focused on the source in the hopes of observing similarly exciting activity in other spectral regions.) Within about ten days the radio intensity of the source had decreased to a normal level, but on 18 September another burst began and two more occurred within a week. The publicity accorded these bursts was immense, occupying, for example, an entire issue of *Nature Physical Science.*

The flux-versus-time curves of the 1972 bursts were found to vary with the frequency at which the observations were made: the lower the frequency, the lower the maximum intensity attained and the later the time at which the maximum intensity occurred (Fig. 5). This frequency dependence suggests that the bursts are caused by injection of relativistic electrons into an expanding volume of plasma. The radio-frequency radiation observed is synchrotron radiation emitted by the electrons as they interact with the magnetic field of the plasma. (A possible source of the relativistic electrons is a burst of gamma rays from the central engine of the compact star, but this idea remains to be tested with simultaneous gamma-ray and radio-frequency observations.) Consistent with this mechanism, which implies that the radio source should expand when a burst occurs, are images acquired with a very-long-baseline interferometer and the VLA during another spate of radio-frequency bursts from Cygnus X-3 in 1982. These observations showed high-intensity radio-frequency emission from extensive, elongated regions that can be interpreted as jets of plasma into which the relativistic electrons are injected. The speed of the jets is at least $0.35c$, where c is the speed of light. Such extremely fast jets have been observed in only one other galactic radio source, the x-ray binary SS 433 (Fig. 6).

Information about the distance to Cygnus X-3 can be derived from absorption lines in the radio-frequency spectra obtained during its bursts. The absorption lines are produced by hydrogen atoms in intervening clouds of interstellar gas. The Doppler shifts of the lines from the normal wavelength of 21 centimeters, coupled with a kinematic model of galactic rotation, yield an estimate of the distance to the source. The best such estimate, a distance of at least 11.6 kiloparsecs, was derived from data taken with the VLA during the 1982 bursts (1 kiloparsec $\cong$ 3260 light-years). There is, however, no reliable upper limit on the distance.

Very recent radio-frequency observations of Cygnus X-3 during its quiet x-ray state suggest the occurrence of low-amplitude radio-frequency flares every 4.95 hours. Like the bursts, the flares are attributed to injection—but in this case periodic injection—of relativistic electrons. It has been suggested that the periodicity of the flares, which is but a few percent longer than the x-ray periodicity, is due to perturbations of the binary separation by the presence in the system of a more widely separated third body.

Optical Radiation. Much of our understanding of x-ray sources comes from data about their visible radiation. Unfortunately, Cygnus X-3 is located in or beyond a dusty spiral arm of our galaxy and cannot be detected with even the most powerful of today's optical telescopes. Models for the origins and observed properties of its x-ray emissions are therefore often based on those developed for similar x-ray

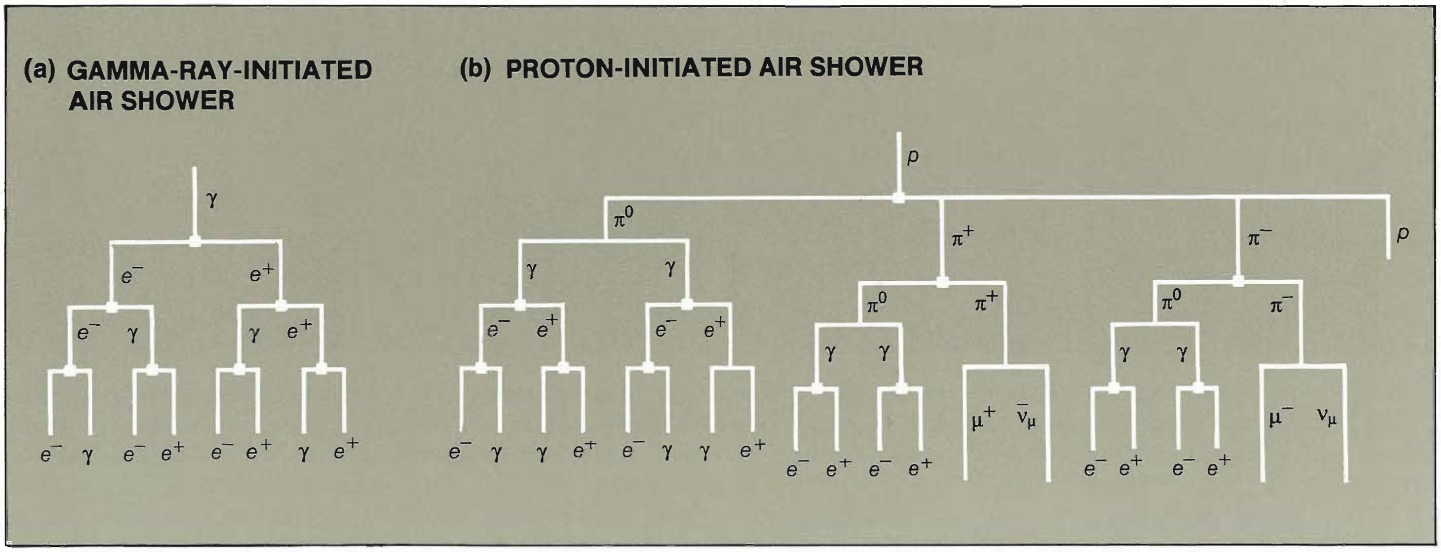


Fig. 7. Examples of air showers initiated in the earth's atmosphere by energetic radiation (photons or particles) from astronomical sources. Such an air shower consists of an increasingly numerous assortment of secondary photons and particles advancing together in a plane perpendicular to the direction of motion of the primary photon or particle. The primaries initiating the air showers fall into two categories. Those in one category, consisting mainly of gamma rays but including neutrinos, neutrons, and other neutral particles, travel through space undeflected by cosmic magnetic fields and arrive at the earth's atmosphere along their original trajectories. Primaries in the other, far more numerous category, consisting mainly of protons but including electrons, alpha particles, and other charged particles, are deflected and arrive along random trajectories. Shown above are early stages of typical air showers initiated by (a) gamma rays and (b) protons. Electrons and positrons are the most abundant secondary particles in both gamma-ray- and proton-initiated air showers, but muons are more abundant in proton-initiated air showers by a factor of about 10. An air shower dissipates when the energies of the secondaries become so low that processes other than those creating new secondaries are dominant. At that point the diameter of the disk-shaped shower, which is proportional to the energy of the primary, can be as large as several kilometers. Air showers that reach the surface of the earth (those initiated by primaries with energies greater than about 10^{14} eV) can be detected with an array of particle detectors, such as scintillation counters. Air showers that do not reach the surface of the earth but come within a certain distance (those initiated by primaries with energies greater than about 10^{11} eV) can be detected on moonless nights with an array of mirrors that gathers the Čerenkov radiation emitted by the secondary particles. Proton-initiated air showers constitute an unavoidable background among which air showers initiated by gamma rays from a source must be detected. The background can be reduced by determining the arrival directions of the primaries from a map of the intensity of the Čerenkov radiation or from the minute differences in times of arrival of the secondary particles at the detectors.

sources that can be studied at optical frequencies.

Cygnus X-3 has been assigned an apparent visual magnitude of no less than 23. It is therefore at least 6 million times fainter than a star of magnitude 6, which is the faintest star the human eye can detect on a dark night.

Infrared Radiation. Shortly after the first of the 1972 radio-frequency bursts from Cygnus X-3, astronomers aimed the 200-inch Hale telescope on Mt. Palomar at the same location and detected infrared radiation at wavelengths between 1.6 and 2.2 microns. (Infrared radiation suffers less severe extinction by dust than does visible or ultraviolet radiation.) Observations during the next year revealed a 4.8-hour periodicity in the infrared source that secured its identification with Cygnus X-3. Large-amplitude flares of infrared radiation were also observed; these lasted for times ranging from a few minutes to one-and-a-half hours. The infrared flares may be radiation from clumps of matter ejected into the jet emerging from Cygnus X-3. If so, the same clumps of matter should give rise to a subsequent radio-flare when they are viewed farther out in the jet. This prediction needs to be tested with simultaneous infrared and radio-frequency observations.

GAMMA-RAY LIGHT CURVE OF CYGNUS X-3

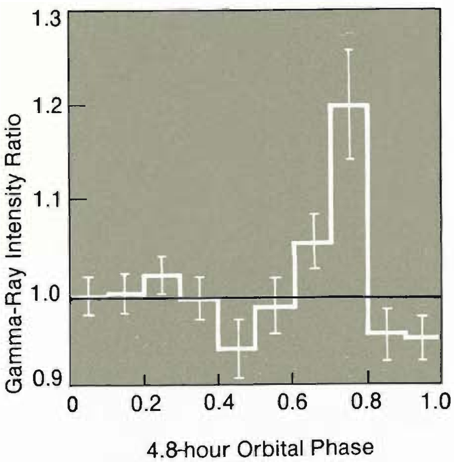


Fig. 8. This light curve is based on detection of Čerenkov radiation emitted by secondary particles in air showers. The energies of the primary gamma rays are greater than about 1 TeV. The ordinate is the ratio of the Čerenkov radiation intensity with the source inside the field of view to that with the source outside the field of view. Note the prominent peak at a phase of about 0.75. Other investigators have reported slightly different phase values for this peak and a second prominent peak at phase values near 0.2. (Figure adapted from S. Danaher, D. J. Fegan, N. A. Porter, and T. C. Weekes,* Nature *289(1981):568.)

Gamma Rays and Cosmic Rays. The term 'gamma ray' is applied to photons with energies greater than about 10^6 eV and covers a wide range of energies. Gamma rays (and high-energy particles) are therefore often subdivided as follows: low-energy, or 'MeV,' gamma rays ($E < 10^8$ eV); high-energy, or 'GeV,' gamma rays (10^8 eV $< E < 10^{11}$ eV); very-high-energy, or 'TeV,' gamma rays (10^{11} eV $< E < 10^{14}$ eV); and ultrahigh-energy, or 'PeV,' gamma rays ($E > 10^{14}$ eV).

It is as a possible source of very-high- and ultrahigh-energy gamma rays that Cygnus X-3 has been accorded a second renaissance of interest. (Other astronomical objects, including the pulsar in the Crab Nebula, the x-ray binary Hercules X-1, the Andromeda Galaxy, and the radio source Centaurus A have also tentatively been identified as sources of TeV and/or PeV gamma rays.)

Low- and high-energy gamma rays from an astronomical source can be detected with satellite-borne instruments (spark chambers, scintillation counters, and Compton telescopes, for example). Whether Cygnus X-3 is a source of such radiation is uncertain. Data gathered in 1973 by the SAS-2 satellite were reported to reveal a 4.8-hour periodicity in the intensity of 35- to 200-MeV gamma rays from the direction of the source, whereas data gathered by the COS-B satellite between 1975 and 1982 were reported to include no gamma rays with energies between 70 and 5000 MeV that could be attributed to the source. This null result is apparently not related to the x-ray state of Cygnus X-3, since the COS-B observations covered both high and low x-ray states.

TeV and PeV gamma rays have such low interaction probabilities that their detection with conventional instruments is not practical. Instead, these gamma rays are observed by detecting the air showers they initiate high in the earth's atmosphere (Fig. 7). A gamma-ray-initiated air shower consists of an assortment of photons and secondary particles (mostly electrons and positrons) that advances toward the earth in a plane perpendicular to the direction of motion of the primary gamma ray. Air showers are detected by sensing either the Čerenkov radiation emitted by the secondary particles or the secondary particles themselves. (The latter technique is limited to air showers that reach the surface of the earth, that is, to those initiated by primaries with an energy of at least 10^{14} eV.)

Experiments aimed at observing TeV and PeV gamma rays from an astronomical source are time-consuming because the flux of such high-energy photons is quite low. The experiments are made even more difficult by the existence of a high, isotropic background of air showers initiated by similarly energetic but far more numerous charged primaries, mainly protons. (The trajectories of charged particles, whatever their source, are randomized by interaction with the inhomogeneous magnetic field of the galaxy.) This background can be reduced by determining the arrival directions of the air showers detected. In addition, if the source being investigated exhibits a periodic intensity variation in other spectral regions, detection of the same periodicity in the intensity of air showers from the direction of the source is conclusive evidence that the primary gamma rays originate from the source.

More than a dozen groups have reported detection of gamma rays from Cygnus X-3 with energies of at least 10^{11} eV. The first report came from a Soviet group in 1972, shortly after the radio-frequency bursts. The tell-tale 4.8-hour periodicity in the gamma-ray flux was subsequently detected by the same group and by American observers. Some investigators report peaks in the gamma-ray light curve at a phase of about 0.2 (relative to the x-ray minimum), others at a phase of about 0.65, and still others at both phases (Fig. 8). (The exact phase values reported for the peaks differ slightly. It has been suggested that the differences may be due to an inherent bias in the data resulting from the close coincidence of a 24-hour day to an integral multiple of the 4.79-hour period of Cygnus X-3. This coincidence, together with the fact that gamma-ray sources are usually observed near zenith, when the signal-to-noise ratio is greatest, implies that data gathered at a particular site during a few days of observation cover only a small portion of the Cygnus X-3 cycle.) Sporadic flux increases lasting on the order of minutes are also observed (Fig. 9).

PeV gamma rays from the direction of Cygnus X-3 and with its 4.8-hour periodicity were first reported in 1983 by a West German group. Their finding has since been verified by groups working in England, the United States, India, and Italy. The PeV gamma rays peak at approximately the same phases as do the TeV gamma rays.

The extremely energetic gamma rays emanating from Cygnus X-3 are undoubtedly the products of interactions between even more energetic particles within the source, mainly protons. Cygnus X-3 is thus the first astronomical object to be identified with reasonable certainty as a source of cosmic rays. (The term 'cosmic ray' is applied to any cosmic radiation with an energy greater than about 10^8 eV. Cosmic rays include protons (92 percent), helium nuclei (6 percent), electrons (1 percent), gamma rays (<0.1 percent), and small percentages of heavier nuclei and other elementary particles.) Calculations based on the observed flux of TeV and PeV gamma rays from Cygnus X-3 indicate that only a very small number of sources of like nature would be required to produce most of the observed high-energy cosmic rays.

The question that has aroused so much interest is how such energetic protons can be produced in Cygnus X-3. Two of several responses to the question invoke accretion as the ultimate energy source: in one of these models, the unipolar inductor model, protons are accelerated by the electric field induced in an accretion disk by the magnetic field of a slowly rotating neutron star (that is, a neutron star with a rotation period of about 1 second); in the other protons are accelerated by shocks in the flow of matter accreting onto a neutron star or a black hole. A third model identifies the energy source as the rotational energy lost by a rapidly rotating, magnetized neutron star (a pulsar) in the process of gradually winding down. Electric fields sufficiently high to accelerate protons to 10^{16} eV are possible near a pulsar with a magnetic field of about 10^{12} gauss and a rotation period of about 10 milliseconds.

Which, if any, of these models is correct remains moot, but the pulsar model seems to have several points in its favor. It may explain the two peaks in the TeV and PeV gamma-ray light curves (as interaction of the proton beam with the atmosphere of the companion star or with some structure on an accretion disk), and, if the acceleration mechanism produces 10^{17}-eV protons, it can reproduce fairly well the observed spectrum of TeV and PeV gamma rays. Furthermore, evidence for the existence of a pulsar in Cygnus X-3 (in the form of a 12.59-millisecond periodicity in the TeV gamma-ray flux) was very recently reported but has not yet been confirmed.

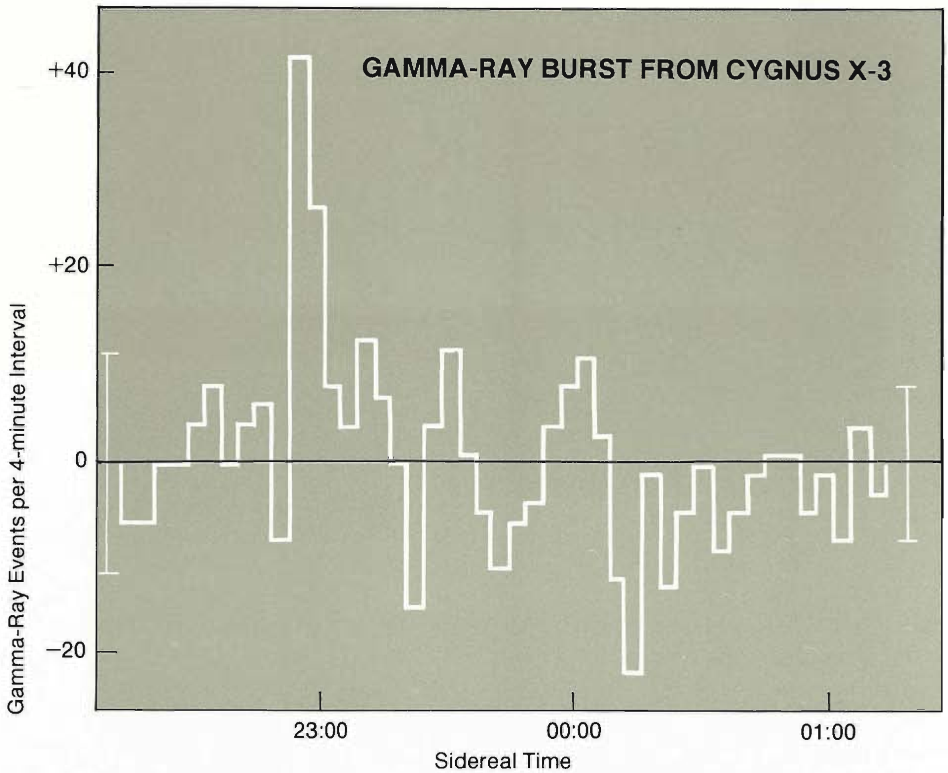


Fig. 9. Cygnus X-3 is an intrinsically variable gamma-ray source, as demonstrated by this plot of an 8-minute burst. The energies of the primary gamma rays are greater than about 1 TeV. (Figure adapted from T. C. Weekes, Astronomy and Astrophysics *121(1983):232.)*

New Particles? Two recent, and controversial, reports have given an additional boost to the resurgence of interest in Cygnus X-3. These reports come from groups searching for evidence of proton decay in detectors far underground, one in the Soudan iron mine in Minnesota and the other in the Mont Blanc Tunnel in Europe. Both groups report that the flux of muons recorded by their detectors exhibits an enhancement in the direction of Cygnus X-3 and with its 4.8-hour periodicity. (Muons are among the secondary particles formed by interaction of primaries with the earth's atmosphere. The relative abundance of muons among the products depends on the identity of the primary; in particular, protons produce a greater number of muons than do gamma rays (see Fig. 7).)

What are the primaries responsible for these muons? The directionality and periodicity of the muons, and thus of the

Fig. 10. Brenda Dingus, a University of Maryland graduate student, examining one of seventy scintillation counters being installed on the grounds of the Los Alamos Meson Physics Facility. The counters compose one element of an experiment aimed at resolving a current controversy about Cygnus X-3. (The experiment is a collaborative effort by the University of Maryland, the University of New Mexico, the University of California, Irvine, and Los Alamos National Laboratory.) The counters are distributed uniformly within a 60-meter-radius circle centered on the other essential element of the experiment—a spark-chamber detector already in use in a study of the scattering of accelerator-produced neutrinos by electrons. The array of scintillation counters will provide highly accurate data about the direction of the air showers detected and thus permit selection of air showers initiated by electrically neutral primaries from Cygnus X-3; the spark-chamber detector will provide data about the muon content of those same air showers. If the muon content of the selected air showers is inconsistent with that theoretically predicted for gamma-ray-initiated air showers, then either the theories of nuclear interactions need modification or some as yet undiscovered neutral particle is originating from Cygnus X-3.

primaries, eliminate as candidates all charged particles, for the reason mentioned above. Neutrons would decay during the 11.6-kiloparsec journey from Cygnus X-3, unless they had the unreasonably high energy of about 10^{18} eV. Neutrinos, oblivious to the intervention of the earth between their source and a detector, would produce a flux of muons that is independent of the position of the source when the observations are made. But the Soudan group reports that the enhancement in muon flux reaches a maximum when Cygnus X-3 is overhead. More detailed arguments provide limits on the masses and lifetimes of the primaries that eliminate all other known neutral particles.

Gamma rays should be the most likely candidates for the primaries, but the enhancement in muon flux reported by the Soudan group is much too large to have been produced by the flux of TeV and PeV gamma rays observed above ground. Moreover, the West German group had previously reported a muon content in air showers initiated by PeV radiation from Cygnus X-3 (presumably but possibly not gamma rays) that also was too high for gamma-ray initiation.

Thus, if the experimental evidence is confirmed, no known particle can be the primary responsible for the enhancements in muon flux. One response to this puzzle has been the conjecture that some previously unobserved neutral particle is emanating from the source. The composition of some of the proposed candidates has led in turn to the suggestion that the compact star in Cygnus X-3 consists primarily of matter containing a substantial fraction of strange quarks (see "Does Cygnus X-3 Contain a Strange Neutron Star?").

However, the statistical analyses of the Soudan and Mont Blanc groups have been challenged, and confidence in their findings has been lessened by more recent reports. Analyses of data from another proton-decay detector (in the Silver King

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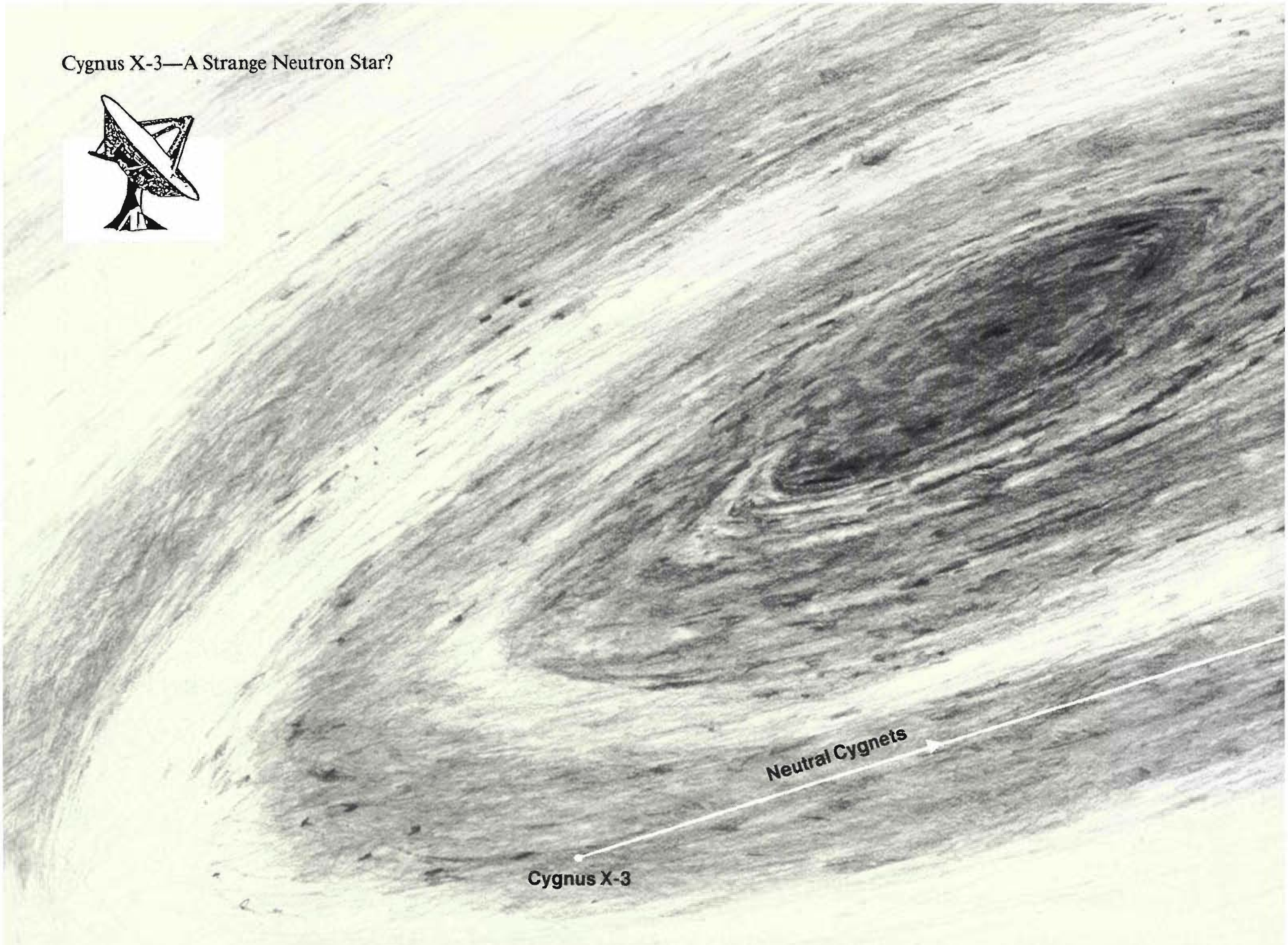
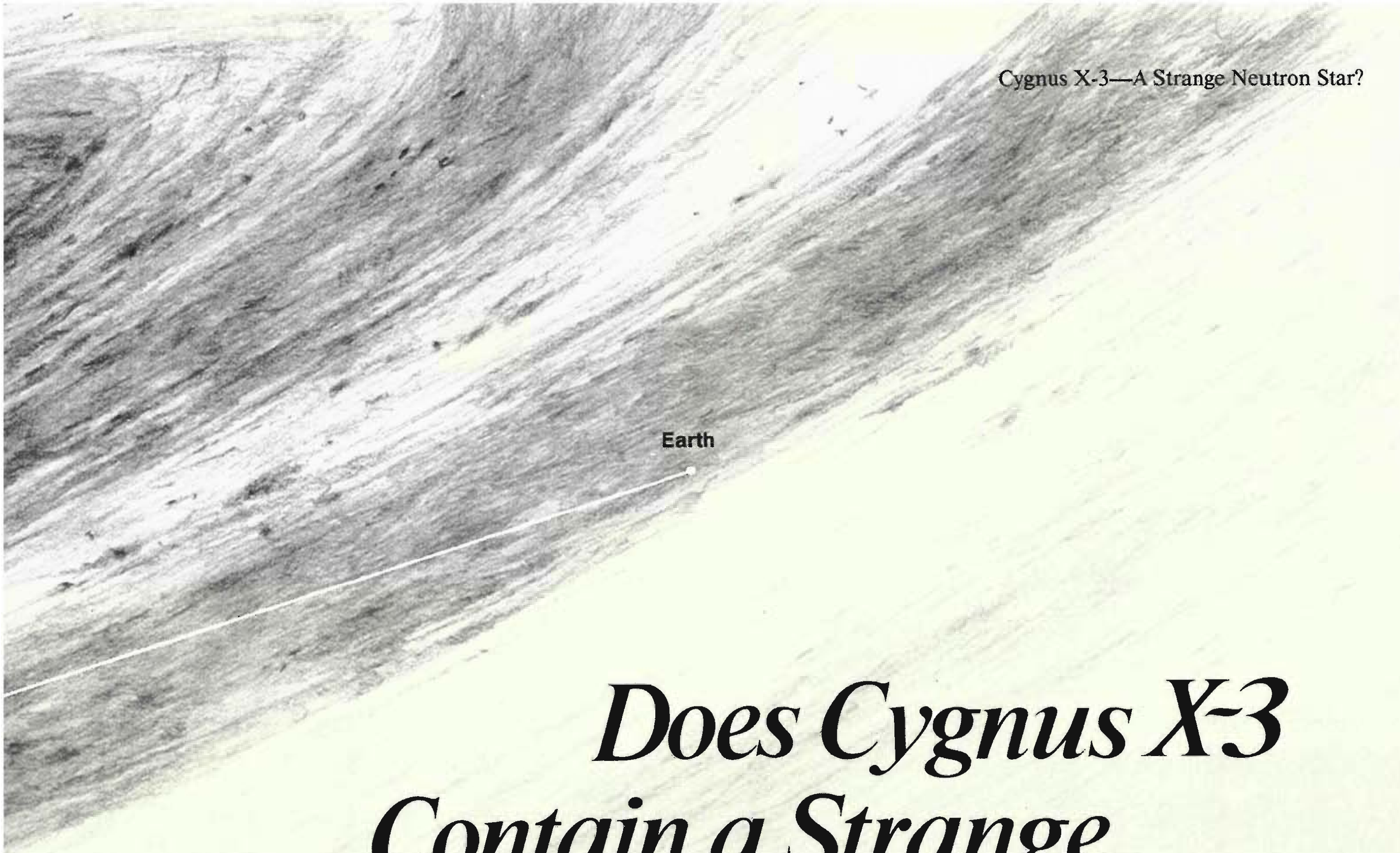


Deep underground proton-decay detectors in the Soudan iron mine in Minnesota and under the Mont Blanc have recorded very energetic muons coming from the direction of Cygnus X-3 with its 4.79-hour periodicity. These observations, if confirmed, present a very challenging puzzle. What is the primary cosmic-ray particle that produces the muons at the earth, and how is such a particle produced in Cygnus X-3? One of the more coherent explanations is that the primaries originate as exotic hadrons (strongly interacting particles, not yet made in laboratories) chipped off the neutron star in Cygnus X-3, a star itself made entirely of matter containing a substantial fraction of strange quarks (Fig. 1).

The detection of a periodic muon signal deep underground constrains the properties of the primary. Firstly, its electric charge must be zero; otherwise the directionality and timing of the signal would be destroyed by galactic magnetic fields. Secondly, the mass of the primary must be less than its energy by a factor of about 10^4; otherwise differences in travel times of primaries with different energies would wash out the periodicity of the primaries and hence that of the muons. (A 100-GeV-mass particle, for example, would arrive about 1 hour sooner if it had an energy of 12 TeV than if it had an energy of 10 TeV (1 GeV = 10^9 eV and 1 TeV = 10^{12} eV).) To produce muons with sufficient energy to penetrate the overlying rock and reach the great depths of the detectors (equivalent to 2 to 5 kilometers of water), the energies of the primaries are likely to be in the range 10 to 100 TeV; the mass of the primaries is therefore likely to be at most 1 to 10 GeV. Lastly, the primary must have a sufficiently long lifetime, of order a year in its rest frame, that it not decay en route from the source. (Lorentz dilation increases the observed lifetime of a rapidly moving particle by the ratio of its energy to its mass.) The known neutral particles with such properties are photons, neutrinos, and neutrons, but arguments presented in the main text appear to rule these out. Briefly, the reported flux of muons is too high to be attributed to gamma rays (high-energy photons), the observed dependence of the muon flux on zenith angle rules out neutrinos, and neutrons would decay in flight unless their energy was unacceptably large.

The only remaining possibility is a previously unobserved particle, a 'cygnet.' The large flux of muons (comparable to the observed flux of gamma rays), and hence of cygnets, suggests that cygnets are



Does Cygnus X-3 Contain a Strange Neutron Star?

by Gordon Baym

Consultant to the Theoretical Division from the University of Illinois

made at a rapid rate through strong interactions rather than through the slower electromagnetic or weak interactions. One promising candidate for this strongly interacting particle is the H particle, earlier proposed by Robert L. Jaffe of MIT, composed of two up, two down, and two strange quarks in a closely bound state; the H is thus a particle with a strangenesss of 2 and a baryon number of 2, the same quantum numbers as two lambda particles. If the mass of the H is less than that of the lambda (1.116 GeV) plus that of the neutron (0.938 GeV), then the lifetime of the H could be sufficiently long for it to be a candidate for the primary, since in this case it could not undergo the rapid decay into a lambda and a neutron. Decay of the H into two neutrons would be very slow since it involves a change in strangeness of 2, a rarer process than a change in strangeness of 1, as when a lambda decays into a nucleon.

How might cygnets be made in Cygnus X-3? To generate the high-energy gamma rays believed responsible for the extensive air showers observed, Cygnus X-3 must have an accelerator capable of producing charged particles with energies up to 10^{16} eV. Cygnets might be produced as the energetic charged particles accelerated from a neutron star interact with the atmosphere of the companion star. However, since the cross section for this process would have to be large to produce them in quantities comparable to those of the gamma rays, we would expect to have seen cygnets produced in laboratory accelerator experiments. (The cygnet mass should be relatively low, so the energy threshold for producing them should be well below the energies available at current accelerators.) A more likely possibility is that the cygnet is accelerated from a neutron star bound to charged particles in the form of an exotic nucleus. Free cygnets could then be released by fragmentation of such a nucleus when it strikes a particle in the atmosphere of the companion star, in a process similar to proton-nucleus fragmentation observed in the laboratory.

The next question is how exotic nuclei might be produced and emitted from a neutron star. A first possibility is that they are made by bombardment of the surface of the neutron star by particles accelerated onto it. (In the electromagnetic acceleration process electron-positron pairs will be produced, and if, for example, positrons are accelerated away, then the electrons will be accelerated back to the surface, at energies of a TeV or greater, and cause substantial spallation of the surface.) This

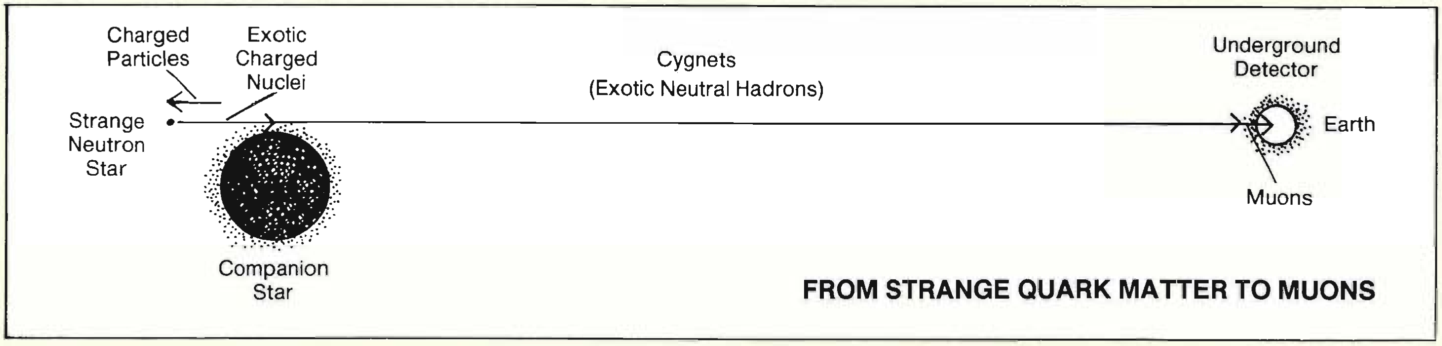


Fig. 1. A scenario for the observation, in underground detectors, of muons with the directionality and periodicity of Cygnus X-3. Particles accelerated onto the surface of a strange neutron star cause ejection of exotic charged nuclei, which are accelerated outward and fragment as they pass through the atmosphere of the companion star. The cygnets released travel undeflected to the earth's atmosphere, where they produce muons that penetrate to the underground detectors.

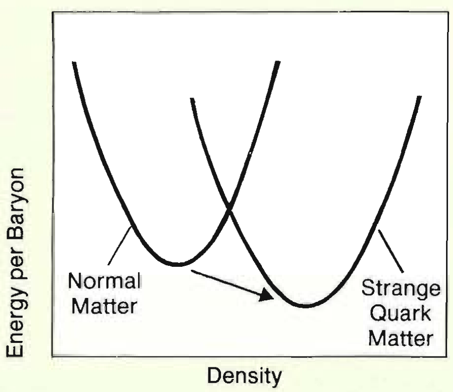


Fig. 2. If, as illustrated here, the minimum in the energy per baryon versus density curve for normal nuclear matter is higher than that for strange quark matter, then normal matter, which in its ground state sits at the minimum of the normal matter curve, would be unstable against transition to strange quark matter. This transition could result in a neutron star composed entirely of strange quark matter.

mechanism might produce exotic nuclei from normal nuclei, but one is faced with the question of why, if correct, it has never been observed in the laboratory. A second possibility is that exotic nuclei are produced in the core of the neutron star and then diffuse to the surface. But the lifetimes of the exotic nuclei must then be exceptionally long, at least the time required for diffusion, of order 10^5 years. The final possibility is that the entire neutron star is made of strange matter, and surface spallation throws exotic nuclei up into the beam of particles accelerated away from the neutron star.

Neutron stars may very well be made of matter containing a substantial fraction of strange quarks if, as Edward Witten of Princeton conjectured, the absolute ground state of matter might not be the familiar material nuclei are made of, but rather is 'strange quark matter' in which the quarks, a substantial fraction of which are strange, are not confined within individual nucleons but are free to roam throughout. By having less zero-point, or Fermi, energy, such matter could be stable compared to ordinary nuclear matter (Fig. 2). (We need not worry about ordinary nuclei turning into strange nuclei if strange matter is the lowest energy state only when a finite percentage of the baryons are strange.)

Imagine then a neutron star being formed (of normal nucleons) in the core of a supernova explosion. At the very high densities in the center (an order of magnitude above the density of laboratory nuclei, some 3×10^4 grams per cubic centimeter), a seed of strange quark matter can form either spontaneously or through a large density fluctuation. If the strange state is lower in energy per baryon than the normal state of nuclear matter, then once formed the seed will begin to convert the matter around it into strange matter, as a fire spreads through flammable material. The 'burning' front would first convert the liquid core of the neutron star to exotic matter; the heat ahead of the front would melt the crust of the neutron star, as well as melt the nuclei in the crust into normal fluid nuclear matter, and within an hour or so the entire star would be converted into a strange neutron star.

One important consequence of this scenario is that if the compact star in Cygnus X-3 is a strange neutron star, then many, if not all, neutron stars should also, as a result of the same burning process, be strange. Strange neutron stars are expected to cool more rapidly than normal stars since they can emit neutrinos more rapidly. This enhanced cooling should be observable in measurements with future x-ray telescopes of the surface temperatures of neutron stars.

The Cygnus X-3 muon data suggest the existence of a new and unusual particle produced in a new and unusual way. If future measurements confirm these data, the underground experiments will have led to a remarkable discovery of new physical phenomena. ■

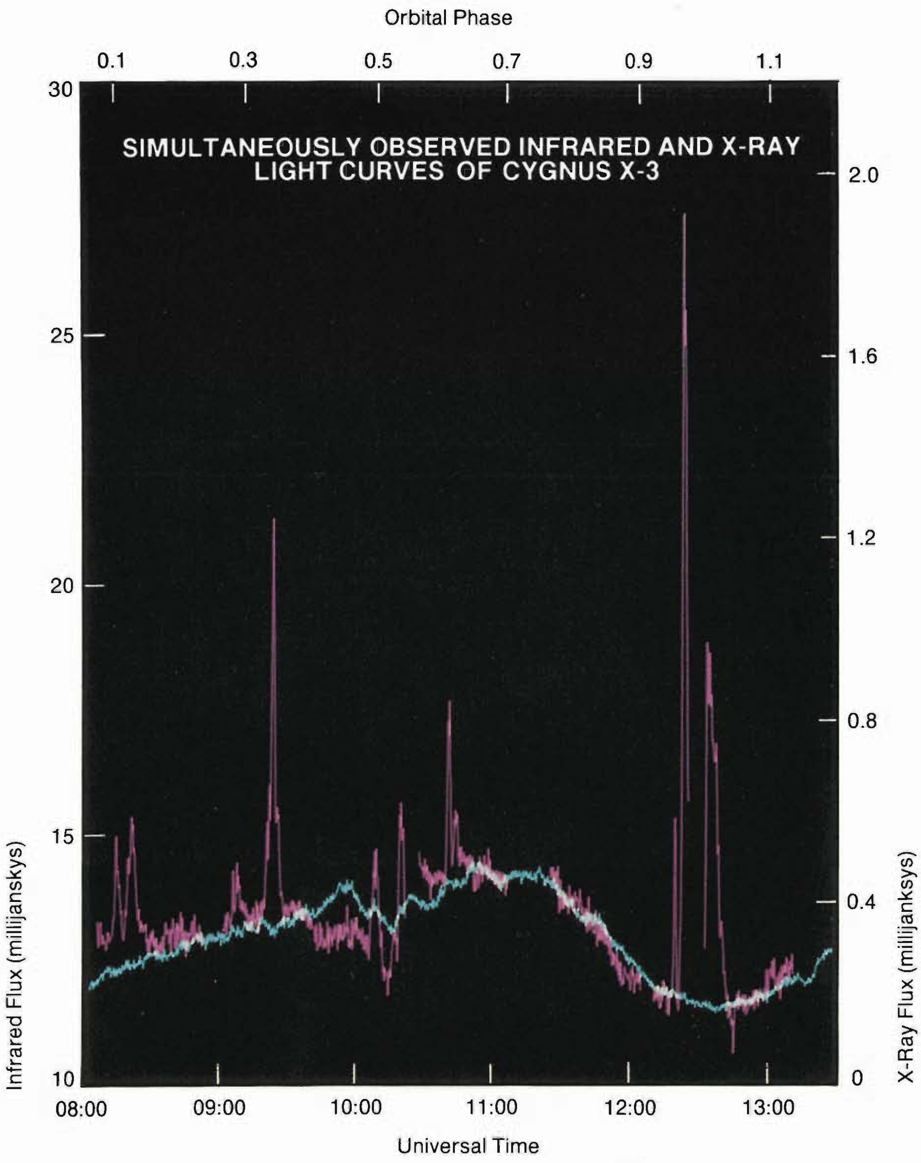


Fig. 11. Simultaneous infrared (red) and x-ray (blue) data taken by the author and K. O. Mason on 2 September 1984 are plotted here with the infrared and x-ray minima superposed to emphasize the almost identical shapes of the orbital modulations. The flares so evident in the infrared data have no apparent x-ray counterparts.

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mine in Utah) and from a neutrino detector (in the Homestake mine in South Dakota) reveal no evidence of a muon flux attributable to primaries from Cygnus X-3, and Japanese investigators report a muon content in air showers initiated by radiation from the direction of the source that is consistent with gamma-ray initiation. Resolution of this muon-content disagreement is a matter of high priority, and a group including Laboratory investigators will soon be carrying out an experiment directed toward that goal (Fig. 10).

Of course, the apparent conflict in the experimental evidence may be due to other factors, such as instrumental error or some intrinsic variability of the source. More data are needed before the new-particle hypothesis can be either accepted or rejected.

Attempts at a More Complete View

The first attempt at simultaneous multi-frequency observation of Cygnus X-3 was made in 1973 by an international group using the Copernicus x-ray satellite and various radio and infrared telescopes. The group collected data between June and October of that year but achieved simultaneity for times totaling only two hours at all three frequency ranges and only several hours at infrared and x-ray frequencies. Unfortunately, these simultaneous data, and somewhat more extensive simultaneous data obtained by the same group in September 1974, were too discontinuous to permit inference of temporal relations among the emissions of the source at different frequency ranges. The data as a whole did, however, reveal some puzzling aspects of the orbital modulation: its constant presence at x-ray frequencies, its lesser magnitude and sometimes absence at infrared frequencies, and its complete absence at radio frequencies. (The coming and going of the infrared orbital modulation in these early data is now attributed to the combined effects of intrinsic variability and the low sensitivity and temporal resolution of the instruments used. The absence of the radio-frequency orbital modulation is attributed to the large size of the radio-emitting region.

Ten years later the author and two colleagues, taking advantage of the greater sensitivity and temporal resolution of the x-ray monitor aboard EXOSAT and the infrared telescope on Mauna Kea, made the second attempt at simultaneous x-ray and infrared observations of Cygnus X-3.

This attempt yielded continuous simultaneous coverage of an entire orbital period. A striking feature of the simultaneous light curves is the clear presence in both of an orbital modulation *of nearly identical shape*, although of different magnitude (Fig. 11). These features must be accounted for in any model of the source.

Two models that may be applicable to Cygnus X-3 are the stellar wind model and the accretion-disk corona model; both can qualitatively explain the identical shapes of the x-ray and infrared modulations, the asymmetry of the modulations about the minima, the lesser magnitude of the infrared modulation, and the greater magnitude of the x-ray modulation at low (less than 6 keV) x-ray energies.

In the stellar wind model x rays from the compact star are scattered into the line of sight by an optically thick cloud of plasma evaporated from the companion star (a stellar wind). In this model the asymmetric modulation of the x rays is attributed to a wake formed in the cloud by radiation pressure of the compact star as it moves through the cloud. To produce x-ray and infrared modulations of the same shape, the cloud must present an effective photosphere of the same radius to both types of radiation. Electron scattering, the dominant mechanism for scattering the x rays, must therefore also be the dominant mechanism for scattering the infrared radiation. The lesser magnitude of the infrared modulation is attributed to dilution by unmodulated bremsstrahlung from the far reaches of the cloud, and the greater magnitude of the x-ray modulation at low x-ray energies is attributed to photoelectric absorption of low-energy x rays within the cloud.

In the accretion-disk corona model (details of which are presented in "X1822−371 and the Accretion-Disk Corona Model") x rays from the compact star are scattered by an optically thick corona evaporated from an accretion disk rather than from the companion star. Asymmetric azimuthal variation in the height of the accretion disk at its outer edge limits the visibility of this corona and causes the asymmetric shape of the x-ray modulation (see Fig. 2). To produce an infrared modulation of the same shape, the infrared radiation must originate from the corona as bremsstrahlung. This model, like the stellar wind model, invokes unmodulated bremsstrahlung and photoelectric absorption to explain the other features of the infrared and x-ray modulations.

The data obtained during the September 1984 observations also revealed a continual succession of infrared flares lasting between 2 and 10 minutes (see Fig. 11). Except for the largest, these flares would not have been detected with the instruments used in 1974. The maximum infrared luminosity of the source during the largest flare, which occurred during the x-ray minimum, was very high, 10^{37} ergs per second. No corresponding x-ray flares are obvious, although they may be obscured by other variable x-ray activity.

The October 1985 multifrequency campaign described at the beginning of this article was launched in the hopes of obtaining longer periods of continuous simultaneous coverage of Cygnus X-3 over a greater frequency range. Serendipitously, the radio, infrared, and x-ray observations were made during an epoch of large radio-frequency flares. Analysis of data from the Soudan proton-decay detector reportedly reveals a correlation between muon events and these flares.

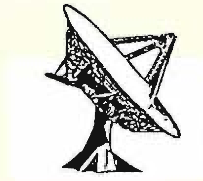
Too little time has elapsed for detailed analyses of all the other data, but we do know that Cygnus X-3 was behaving unusually not only at radio frequencies but also at infrared and x-ray frequencies. Its x-ray flux was greater than ever before, and, compared to the previous year, its infrared flux was greater by a factor of 2 to 4 and its infrared flares were more intense and lasted longer. Apparently infrared flares, like radio flares, are characterized by a large spectrum of durations and amplitudes. Analyses of the data will focus on searching for correlations between the times at which infrared and radio flares begin and peak, between x-ray and gamma-ray activity, and between spectral changes and flux changes.

The Future

Many other astronomical objects deserve simultaneous multifrequency observation, and, indeed, some have received it. The results, especially in the case of flare stars and BL Lacertae objects, have been most informative. But the experiments, as now conducted, are difficult to organize and expensive of limited resources, such as human time, telescope time, money, and fuel for maneuvering satellites into position. Furthermore, the goal of achieving simultaneity is often not met: scheduling problems, failure of one or more of the detectors or data-acquisition systems, and lack of cooperation by the weather can lead to gaps in what was intended as simultaneous coverage.

These difficulties could be alleviated by outfitting satellites with as many detectors as possible, each covering a different frequency range. In line with this goal, Laboratory astronomers and collaborators from abroad have prepared a proposal for addition of optical and ultraviolet monitors to future American and European x-ray satellites. Another possibility being considered is the mounting of a multifrequency observing platform on the American space station now being planned.

Such arrays of instruments will make simultaneous coverage much easier and more certain and, when directed toward a particular astronomical object, will accelerate progress toward its understanding. An equally, if not more, compelling argument for deployment of detectors in this manner lies in the history of astronomy, and all of science. X-ray sources, pulsars, sources of gamma-ray bursts, the microwave background—all were discovered by instruments aimed at the heavens for other purposes. We cannot know in advance what there is to know, but we dare not let pass the opportunity to discover it. ■



X1822 – 371 and the Accretion-Disk Corona Model

by France Anne-Dominic Córdova

The galactic x-ray source known by its coordinates as X1822–371 is of particular interest because its x-ray light curve, like that of Cygnus X-3, is unusual for an eclipsing binary. However, X1822–371, unlike Cygnus X-3, can be observed at optical frequencies, and much information basic to the development of models for x-ray binaries is obtained from optical data. The models fashioned for X1822–371 illustrate well how astrophysicists infer the existence and properties of structures they cannot image directly.

X1822–371 first came to notice in the early seventies through detection of its x rays by the Uhuru satellite. Not until 1978, however, was its faint optical counterpart identified. A 5.57-hour periodicity in the intensity of its continuum optical radiation was discovered soon thereafter, and the same periodicity was subsequently detected in its x-ray, ultraviolet, and infrared emissions and in the intensities and Doppler shifts of its optical emission lines. The periodic variation in the Doppler shifts permitted positive identification of the source as a binary system. (In contrast, Cygnus X-3 can at present only be presumed to be a binary system.)

The picture of X1822–371 that is most consistent with spectroscopic and photometric studies of its optical radiation is that of a binary system composed of a low-mass, late-spectral-type companion star filling its Roche lobe, an accretion disk, and a neutron star emitting x rays as matter accretes onto its surface from the companion star. Estimates for the masses and radii of the component stars and for the binary separation are listed in the accompanying table.

Qualitative attempts by K. O. Mason and colleagues to explain the optical light curve of X1822–371 led to suggestions about the source of the optical radiation and the existence in the system of some occulting structure in addition to the companion star. As shown in Fig. 1, the optical light curve exhibits two dips in intensity: a narrow dip to the minimum intensity and a broader asymmetric dip. The near equality of the fractional width (at half minimum) of the narrow dip to the angle subtended by the companion star at the neutron star suggested that this feature was due to occultation by the companion star of a luminous accretion disk in a system with a binary inclination near 90°. (The inclination of a binary system is the angle between the axis of rotation of the system and the line of sight.) The shape of the broad dip suggested that the luminous region was being obscured by some extended structure, perhaps a bulge on the outer edge of the accretion disk or the stream of accreting matter between the companion star and the disk.

These suggestions, together with the observational data of many astronomers, led to the development by N. E. White and S. S. Holt of a model (the accretion-disk corona model) for the x-ray light curve of X1822–371, which, like the optical light curve, exhibits a narrow and a broad dip in intensity (see Fig. 1). In this model the narrow dip in the x-ray light curve is attributed to occultation by the companion star of an extended x-ray source centered on the neutron star. This source—a corona of x-ray-scattering plasma extending above and below the plane of the accretion disk—may be formed as matter is evaporated from the inner portion of the accretion disk by the radiation pressure of the neutron star. Compton scattering was assumed to be the dominant scattering mechanism in the corona, since the observed x-ray spectrum of X1822–371 could be interpreted as resulting from Comptonization of a hard x-ray spectrum by an optically thick corona.

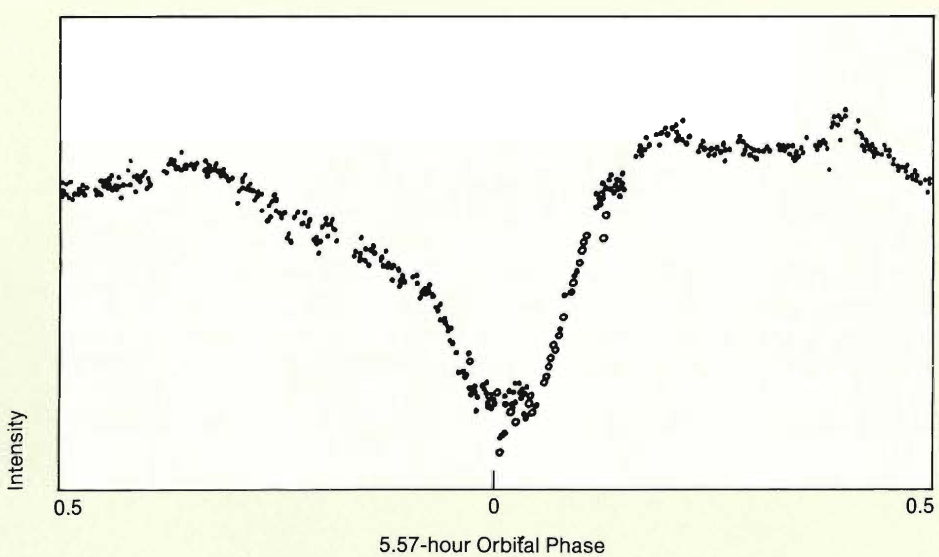
White and Holt showed how the broad dip in the x-ray light curve could arise from occultation of the corona by a prominent bulge on the outer edge of the accretion disk at the confluence of the disk and the stream of accreting matter. This bulge may be caused by turbulence. A smaller

Table

Basic properties of the x-ray binary X1822–371. The mass listed for the neutron star is typical of those measured for pulsating neutron stars; the radius is that derived from theoretical calculations. The binary inclination and the distance to the source were inferred from a fit of the optical light curve to the accretion-disk corona model. The other properties were derived from spectroscopic and photometric studies of optical radiation from the source. Complete references are provided in the bibliography at the end of the article.

Property	Value	Reference
Neutron star mass	$\sim 1.4 M_\odot$	
Neutron star radius	$\sim$10 kilometers	
Companion star mass	$\sim 0.25 M_\odot$	Mason et al. 1982
Companion star radius	$0.5 R_\odot$ to $0.7 R_\odot$	Mason et al. 1980
Binary separation	$\sim 2 R_\odot$	Mason et al. 1980
Binary inclination	76° to 84°	Mason and Córdova 1982
Distance	2 to 3 kiloparsecs	Mason and Córdova 1982

OPTICAL LIGHT CURVE OF X1822–371



X-RAY LIGHT CURVE OF X1822–371

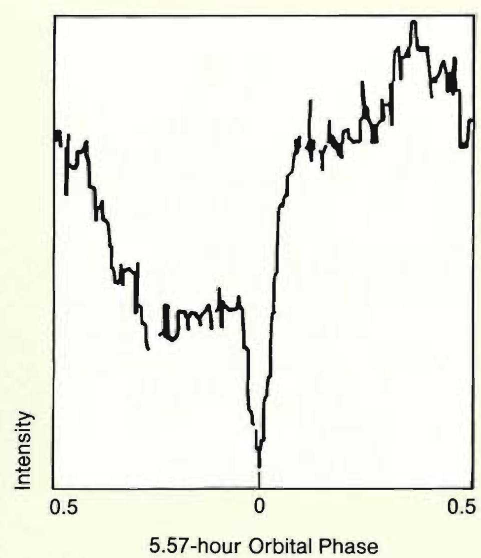


Fig. 1. Both the optical and the x-ray light curves of X1822–371 show a narrow dip to the minimum intensity convoluted with an earlier, broader dip. Both curves can be reproduced with the accretion-disk corona model (see text). (Optical light curve adapted from K. O. Mason, J. Middleditch, J. E. Nelson, N. E. White, P. Seitzer, I. R. Tuohy, and L. K. Hunt, The Astrophysical Journal *242(1980):L109. X-ray light curve adapted from N. White and K. Mason,* Space Science Reviews *40(1985):167.)*

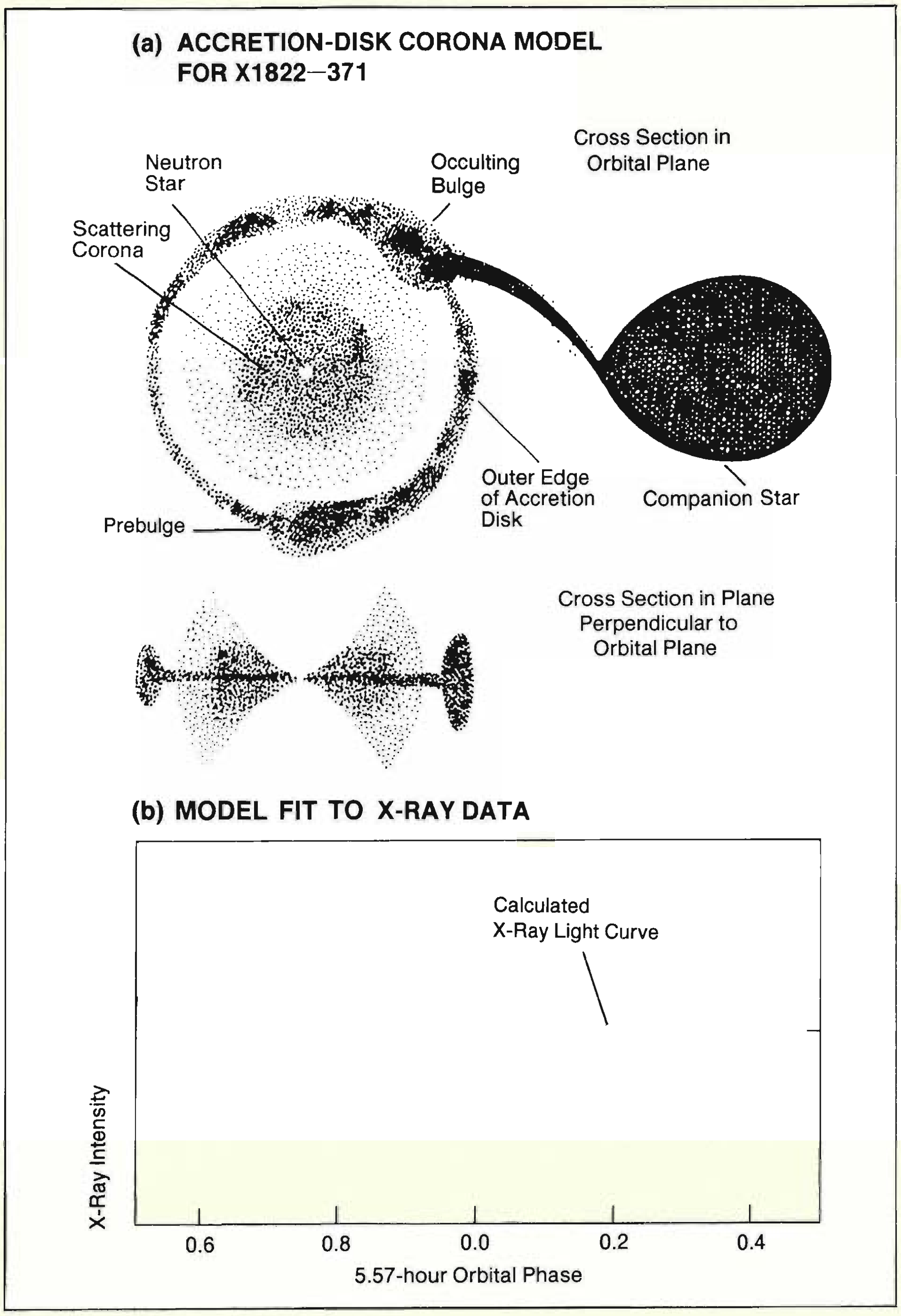


Fig. 2. An accretion-disk corona model for X1822–371 containing the structural features shown in (a), namely, a scattering corona within the disk and occulting bulges on the outer rim of the disk, can be fitted, as shown in (b), to the x-ray light curve with appropriate choices for the geometric parameters that appear in the model (see text). (Adapted from N. E. White and S. S. Holt, The Astrophysical Journal *257(1982):318.)*

bulge upstream of the prominent bulge is also included in their model.

The parameters that can be varied in fitting an accretion-disk corona model to a light curve include the inclination of the binary, the radii of the corona and of the disk, and the height(s) of the bulge(s). From a fit of the model to the x-ray light curve, White and Holt inferred that the inclination of the binary is about 75°, the height of the large bulge is between $0.15R_\odot$ and $0.3R_\odot$, the height of the small bulge is half that of the large bulge, the radius of the disk is between $0.6R_\odot$ and $0.7R_\odot$, and the radius of the corona is about $0.3R_\odot$. Figure 2 illustrates their model and its fit to the x-ray light curve.

K. O. Mason and the author have found that the accretion-disk corona model also provides good fits to the light curves of X1822–371 in spectral regions other than the x-ray, namely, the infrared, optical, and ultraviolet regions. (Figure 3 shows the fit to the optical light curve.) In their calculations they included contributions to the total radiation from four regions: the accretion disk, the inner surface of the thickened outer rim of the disk, the surface of the companion star facing the neutron star (all being heated by x rays from the neutron star), and the outer surface of the rim. The contribution from each region is modulated differently by orbital motion. Reprocessed x rays are assumed to dominate the radiation from the accretion disk and the inner surface of its rim. They found that the best fits to the three light curves were obtained with a binary inclination of about 80°. Their fit to the optical light curve yielded values for the areas of emitting regions; these areas were used to infer a distance to the source of between 2 and 3 kiloparsecs.

Mason and the author also fitted the observed near-infrared to far-ultraviolet spectrum of X1822–371 (at maximum light) to a blackbody spectral model. They found that the source could be approximated well by a 27,000-kelvin blackbody slightly reddened by interstellar absorption. The x-ray luminosity required to heat

X1822–371

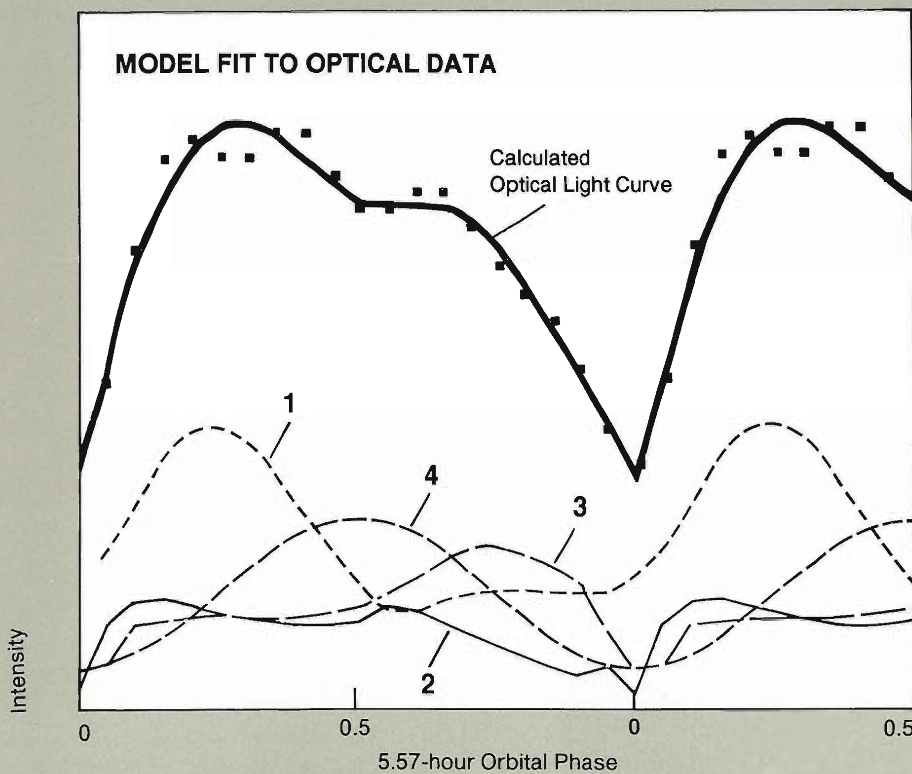


Fig. 3. If the optical radiation from X1822–371 is assumed to consist of a weighted sum of contributions from four luminous regions, its optical light curve can be reproduced well by the accretion-disk corona model. The luminous regions are (1) the inner surface of the thickened rim of the accretion disk, (2) the accretion disk, (3) the outer surface of the thickened rim of the accretion disk, and (4) the face of the companion star illuminated by the neutron star. The contribution from each region is modulated as shown by the companion star and structures on the accretion disk. (Figure adapted from Keith O. Mason and France A. Córdova, **The Astrophysical Journal** ***262(1982):253.)***

the disk to this temperature is about 10^{36} ergs per second, a value that is consistent with the observed x-ray flux and the estimated distance to the source.

Although the x-ray light curve of Cygnus X-3 does not exhibit a narrow dip in intensity, it does exhibit a broad dip that cannot be attributed to photoelectric absorption. The gross morphology of this broad dip can be reproduced with the accretion-disk corona model. The fit to the x-ray light curve yields the following picture of the system: an inclination of about 70°; a corona with a radius equal to three-quarters of the radius of the accretion disk; and, on the outer edge of the disk, a large bulge with a height equal to at least half the radius of the disk and subtending an angle of about 40° at the compact star. The author and colleagues are currently analyzing recent infrared data for Cygnus X-3 to see if its infrared light curve also can be reproduced with this model. ■

AUTHOR

France Anne-Dominic Córdova received a B.A. in English literature from Stanford University and, in 1979, a Ph.D. in physics from the California Institute of Technology. She immediately joined the Laboratory as a staff member in what is now the Space Astronomy and Astrophysics Group. In 1983 she took a year's professional leave of absence to enjoy a NATO postdoctoral fellowship at the United Kingdom's Mullard Space Science Laboratory, where she analyzed data from the European Space Agency's EXOSAT satellite. She has made astronomical observations in nearly every region of the electromagnetic spectrum and has written over fifty professional papers and popular astronomy articles. In 1984 she was named by *Science Digest* as one of America's hundred brightest scientists under forty. She has served on the National Science Foundation's Advisory Council and is at present a member of the International Users Committee for West Germany's Roentgen satellite and president of the Los Alamos Mountaineers.

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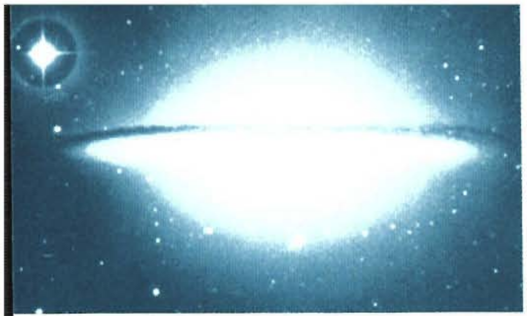
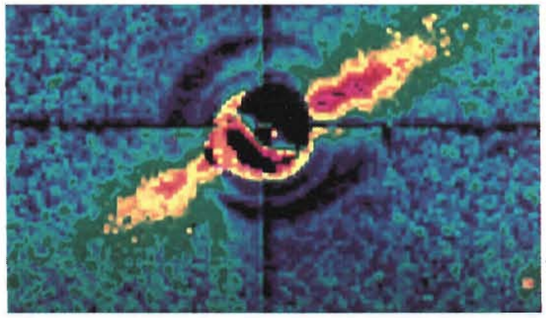
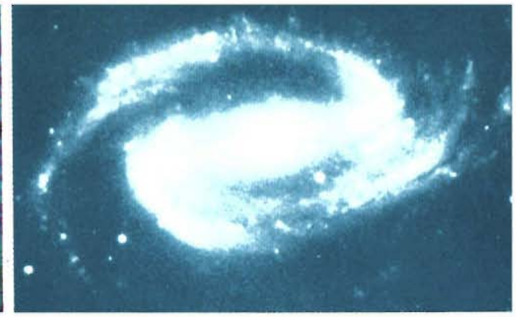
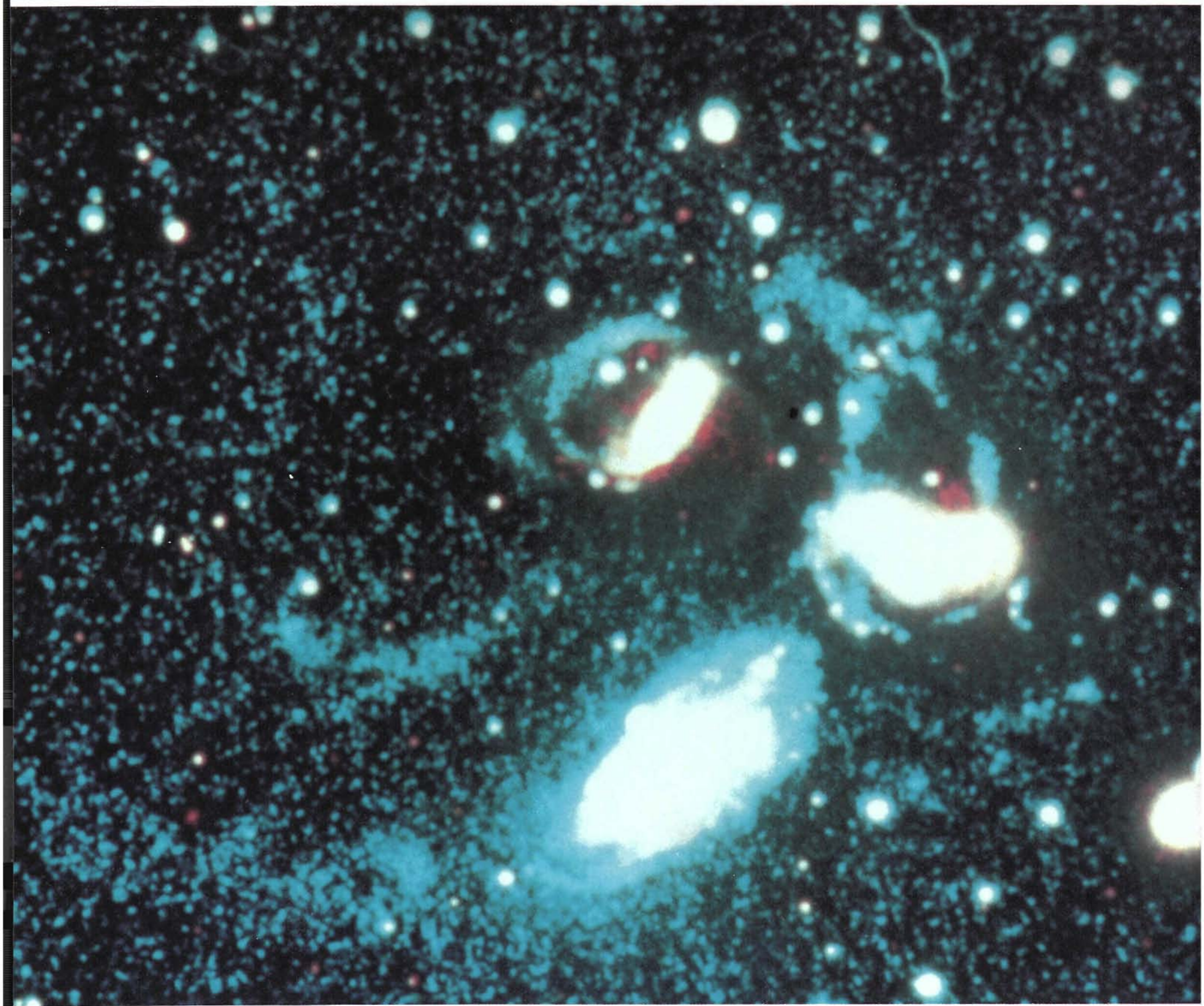
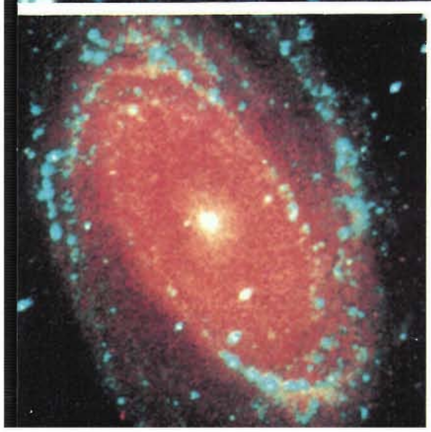
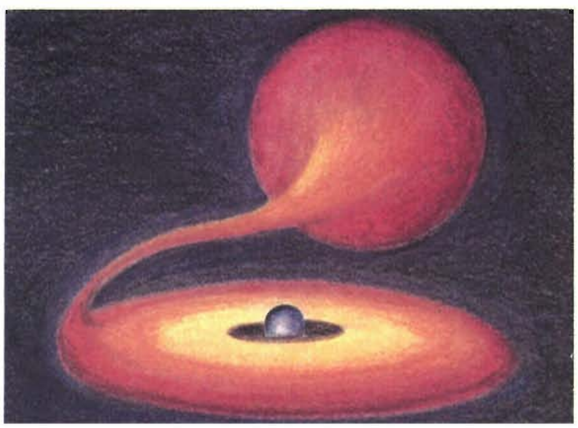
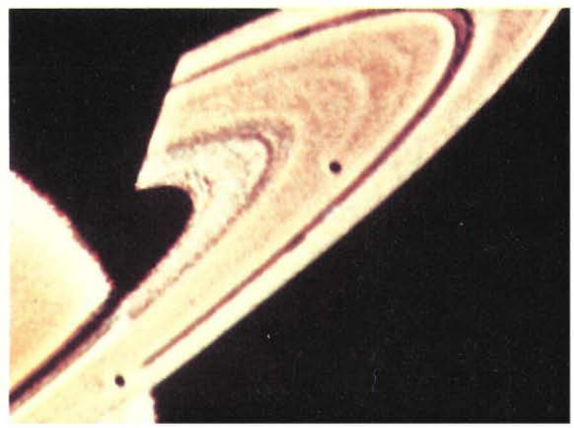

Angular Momentum the cosmic pollutant

by Stirling A. Colgate and Albert G. Petschek

There seems to be too much angular momentum in the universe to allow the formation of stars or the accretion of matter onto variable x-ray sources. This fundamental problem begs for solution.

When we have too much of something and cannot find a way of getting rid of it, we often think of it as a pollutant. In the game of concentration and collapse of matter in the universe from clouds of gas to clusters of galaxies, galaxies, stars, planets, and black holes, angular momentum is the "pollutant" that prevents the game from being played to the absolute limit, namely, collapse into one awesome black hole for each cluster-sized cloud condensed from the early universe. Only at the scale of the whole universe does the energy in the Hubble expansion of the universe prevent collapse, independent of angular momentum constraints. On smaller scales there seems to be too much angular momentum to allow the collapse of clouds into dense objects.

◀ ***Examples of relatively dense astrophysical objects whose disk-like shapes indicate they have a net angular momentum. The central figure is Stephan's Quintet, a group of five interacting galaxies. Along the top from left to right are an edge-on view of the spiral galaxy NGC 4594, the star Beta Pictoris surrounded by a disk of dust, and the barred spiral galaxy NGC 1300. Along the bottom from left to right are the galaxy M81, an artist's conception of an x-ray binary, and the rings of Saturn. (Photo credits are given at the end of the article.)***

Yet our universe is populated by planets, stars, and black holes. How does nature get rid of the cosmic pollutant?

Models proposed for variable x-ray sources give a strong clue to this longstanding puzzle (see "X-Ray Variability in Astrophysics"). But before we restrict ourselves to x-ray variables, let's look at the problem more generally.

Angular Momentum, Weights, and Noncosmological Strings

The angular momentum of a weight of mass m whirled at velocity v at the end of a string of length R is mvR. Under ideal circumstances, that is, a rigid support for the string, no air friction, and no other external torques, the weight will continue to circle at the same velocity forever. In other words, its angular momentum $J = mvR$ is conserved. If the string is shortened, by pulling it through the support, then since the angular momentum must remain constant, the weight will speed up to a higher angular frequency $\omega = v/R$.

The inward force necessary to keep the weight moving in a circular path, $F_R = mv^2/R = m\omega^2R$, is supplied by the tension in the string. Since $F_R = J^2/mR^3$ in terms of the angular momentum, we see that the tension in the string increases very rapidly, as R^{-3}, as the string is shortened. In the cosmic game of collapse, the analogue of the tension in the string is the attractive gravitational force, which is proportional to R^{-2}. Since the required inward force goes as R^{-3}, while the available gravitational force goes as R^{-2}, there is bound to be a point beyond which gravity is unable to cause further collapse. This is the basis of a stable Keplerian orbit, like that of the earth around the sun or that of accreting matter around a compact star in an x-ray binary. Once in a stable orbit, the only way for matter to move farther inward is to lose angular momentum, but the puzzle is how? We also would like to estimate how much angular momentum has to be lost by whatever mechanism we devise.

Angular Momentum and the Universe

The universe as a whole does not seem to be rotating, as evidenced by the fact that the blackbody radiation believed to be a relic of the early universe is isotropic to better than one part in 10^4. Moreover, Tyson has found the orientations of a very large number of galaxies to be random. Since the net angular momentum appears to be zero over very large scales, the pollution is not as bad as it could be. Our problem is restricted to local patches of the universe where matter collapses to form relatively dense rotating objects such as those shown in the opening figure.

Galaxies Are Not a Problem. Let us consider the specific angular momentum $J_s = vR$ (angular momentum per unit mass) of a typical, modestly sized, spiral galaxy. The rotational velocity of matter at its outer edge, determined from the Doppler shifts of spectroscopic lines, is about 150 kilometers per second, and its radius is about 10 kiloparsecs ($\sim 3 \times 10^{22}$ centimeters),* so $J_s \approx 5 \times 10^{29}$ centimeters squared per second. Suppose that, before condensing, the galactic matter occupied a space with a radius equal to one-half the average distance between galaxies, roughly 3 megaparsecs, or 300 times the galactic radius. If angular momentum was conserved in the collapse to the 10-kiloparsec galactic radius, the initial velocity of the matter must have been less by a factor of 300, or about 5×10^4 centimeters per second. This velocity, which is roughly the speed of sound in hydrogen at 150 kelvins, seems to be a reasonable value for the velocity of the turbulent eddies that must have existed when galaxies began to form. In fact, theoretical calculations suggest that density fluctuations in the early universe may produce velocities of this order. Theoreticians thus regard angular momentum in spiral galaxies not as a pollutant but as a much sought-after relic of an earlier history. This reasonable state of affairs is in sharp contrast to the problem angular momentum poses in the making of a star. Angular momentum may also be a problem in the formation of nearly spherical "elliptical" galaxies, which seem to have very little total angular momentum.

Collapse to Stars. The density of matter in our own galaxy before any of the matter collapsed into stars was roughly 0.1 to 1 hydrogen atom per cubic centimeter, or about 10^{-24} gram per cubic centimeter. To form a star, this dilute matter must have collapsed to a density of about 1 gram per cubic centimeter, an increase by a factor of 10^{24}. The radius would have decreased by a factor of 10^8, the cube root of the density ratio. The Keplerian velocity at the stellar radius is about 10^6 to 10^7 centimeters per second, so the initial velocity needed to conserve angular momentum must have been 10^8 times smaller, or 10^{-2} to 10^{-1} centimeter per second. This velocity is unreasonably small for the gas in a turbulent rotating galaxy. A more reasonable velocity for gas clouds, or even for galactic rotation, over the radius of the space from which the stellar matter ought to have been drawn, would be 10^5 to 10^6 centimeters per second. With this value for the velocity, coordinated motion of even a small fraction of the matter will introduce too much angular momentum, by a factor of 10^6 to 10^8, to allow collapse. This immense amount of excess angular momentum must somehow have been dumped before collapse.

For collapse to a neutron star, 10^{14} times more dense than a normal star, the problem would be worse by a factor equal to the sixth root of 10^{14}. (Since the Keplerian velocity is proportional to $R^{-1/2}$, $J_s = vR$ is proportional to $R^{1/2}$, or $\rho^{-1/6}$.) Thus we have another factor of about 100, or a total of 10^{10} times too much angular momentum.

We have discussed only the initial and final states involved in star formation, both of which are spherical. It must not be imagined, however, that the collapse is spherical throughout. Angular momentum conservation prevents collapse only in the directions perpendicular to the rotation axis; collapse parallel to the rotation axis is not inhibited and thus occurs first. This leads to formation of a disk whose radius is almost as large as the initial radius of the cloud. But the disk still has the large initial angular momentum that seems to prevent further collapse. Where and what are the galactic dumping grounds for this angular momentum?

Magnetic Fields

Only external torques can alter the angular momentum of a system. An obvious way to apply a global external torque to dilute ionized matter is through magnetic fields. Indeed this is an often-invoked panacea for the problem. The difficulty is that magnetic fields with the necessary strength and dimension are not observed in the universe. Furthermore, even if our estimates of magnetic field strengths (obtained from observations of the Faraday rotation of the polarization angle of radio waves caused by their passage through a magnetic field) are erroneous, we are faced with the following dilemma. If matter is to be strongly affected by magnetic fields, as is reasonable for partially or fully ionized matter, it is also reasonable that the matter is strongly tied to the field lines. Hence, as a not so extraneous conclusion, magnetic confinement fusion should be simple. The fact that it is not means that ionized matter escapes magnetic fields deceptively easily. Suppose, to the contrary, that matter and field are strongly coupled. Then purely two-dimensional radial collapse by our factor of 10^8 would mean that a region of uniform galactic field of 3×10^{-6} gauss would be compressed by a factor of 10^{16} in the newly formed star, and the field would increase to 3×10^{10} gauss. This is too much field by many orders of magnitude. The pressure of such a field, $B^2/8\pi \approx 4 \times 10^{19}$ dynes per square centimeter, is larger than the pressure inside the newly formed star by a factor of 10^4 to 10^6. Hence, magnetic field must escape easily from the collapsing matter even though it cannot escape too easily if it is to remove the extra angular momentum. Such a balance between field escape and field trapping seems most unlikely—although possible.

Thin Keplerian Accretion Disks

The hydrodynamics of thin accretion disks provides a more plausible mechanism for getting rid of angular momen-

The unit of distance called a parsec is equal to about 3×10^{18} centimeters; its name is derived from parallax-second. A parsec is the distance at which the direction to an object, viewed from the earth at opposite phases of the earth's orbit around the sun, changes by 1 second of arc. The pointing accuracy of a typical old-fashioned telescope is about 1 second of arc.

AZIMUTHAL VELOCITIES OF ROTATING WHEEL AND KEPLERIAN DISK

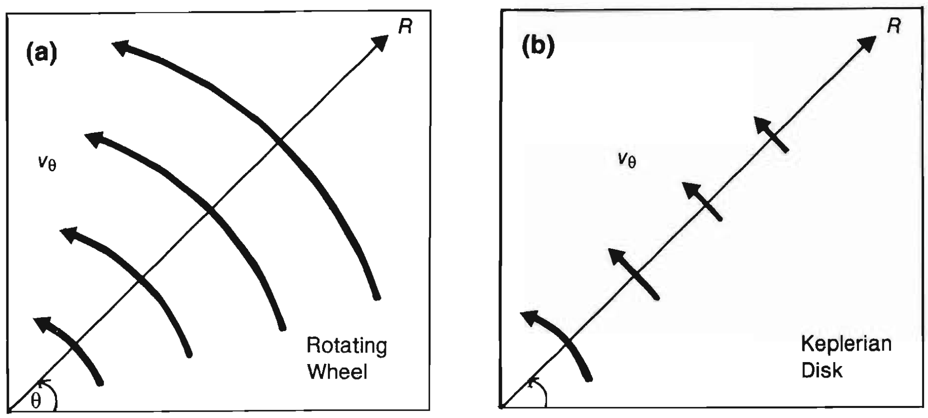

Fig. 1. Distribution of azimuthal velocities v_θ on (a) a rotating wheel and (b) a Keplerian disk. In a rotating wheel $v_\theta \propto R$ and $J_s \propto R^2$, so angular momentum is concentrated at the periphery. In a Keplerian disk $v_\theta \propto R^{-1/2}$ and $J_s \propto R^{1/2}$. The velocity shear in the disk tends to equalize the velocities and therefore transport angular momentum toward the periphery, that is, make the disk more like a wheel. In a gaseous disk ordinary molecular diffusion is too slow to explain the transport of angular momentum required for star formation. ◀

tum, or at least for allowing its transport outward as matter accretes toward a central point.

In variable x-ray sources and cataclysmic variables, accretion disks form around small, dense stars as matter from a companion star is pulled toward the compact object and trapped into orbit by the strong gravitational field. Such accretion disks resemble the rings around Saturn, but, whereas the rings around Saturn are evidently composed of solid chunks of matter that occasionally bump into one another, an accretion disk is composed of gaseous matter. The gaseous disks that eventually collapse to form isolated stars are thought to be quite similar.

Let us look at a likely state for matter that has partially collapsed and run into the angular momentum barrier. As explained earlier, it will go into a stable Keplerian orbit. Now matter of slightly different angular momenta will go into orbit at slightly larger or smaller radii and have slightly different velocities. If this matter is in gaseous form, it will "rub" with this differential velocity, and the friction will lead to a torque and hence a change in angular momentum. The direction of the rub tends to make the gaseous disk rotate more like a solid body or a wheel. In other words, matter at the periphery tends to speed up, increasing its angular momentum, while matter near the center slows down, decreasing its angular momentum (Fig. 1). The friction does just what we want—it transports angular momentum from the inside to the outside of the disk, allowing the inner matter to collapse and the outer matter—a small fraction—to be spun up and flung off, carrying with it all the excess angular momentum. So what's the rub?

The interaction between adjacent mass elements moving at different velocities can be characterized by the kinematic viscosity D (the ratio of dynamic viscosity to density). We use the unlikely symbol D for kinematic viscosity because this is really a diffusion coefficient. It describes how fast a viscous wave (velocity shear) relaxes due to molecular motion. To carry out an order-of-magnitude calculation, we use the kinematic viscosity of hydrogen at room temperature, which (in centimeters squared per second) happens to be almost equal to $10^{-3}/\rho$ when the density ρ is expressed in grams per cubic centimeter. As in any diffusion phenomenon, the relaxation time τ equals the square of the diffusion distance divided by the diffusion coefficient, or R^2/D. Combining these equations with an expression for the density, we find for τ, the time required for angular momentum to "diffuse" out of the disk, a value of 3×10^{17} seconds times the mass of the central object (in solar masses) and divided by the thickness of the disk (in parsecs). The thickness of the disk is much less than its radius, which must become much smaller than 1 parsec in the course of star formation. Hence the time required to form a star in this way would exceed the age of the universe, at most 6×10^{17} seconds, by several factors of ten. Yet stars abound. Clearly we need a better rub or more viscosity.

The Rub, or α

A model that assumes a large viscosity was invented by Shakura and Sunyaev to explain the apparently rapid accretion of matter from a disk onto a compact star in x-ray and cataclysmic variables. This model invokes turbulence as the source of the viscosity but does not describe how the turbulence is driven. The strength of the turbulence is parameterized by a coefficient α, which can be varied between 0 and 1. Calculations based on this hypothetical turbulent viscosity have been very successful in duplicating the apparent accretion rates in x-ray variables. The value of α turns out to be quite large, implying that the accretion disk is highly turbulent. Such calculations, and even more detailed calculations of accretion in cataclysmic variables, strongly suggest the validity of the model. Thus the elusive friction in Keplerian disks may have been identified. If so, we know how nature gets rid of the excess angular momentum that would otherwise prevent the formation of stars and hence us.

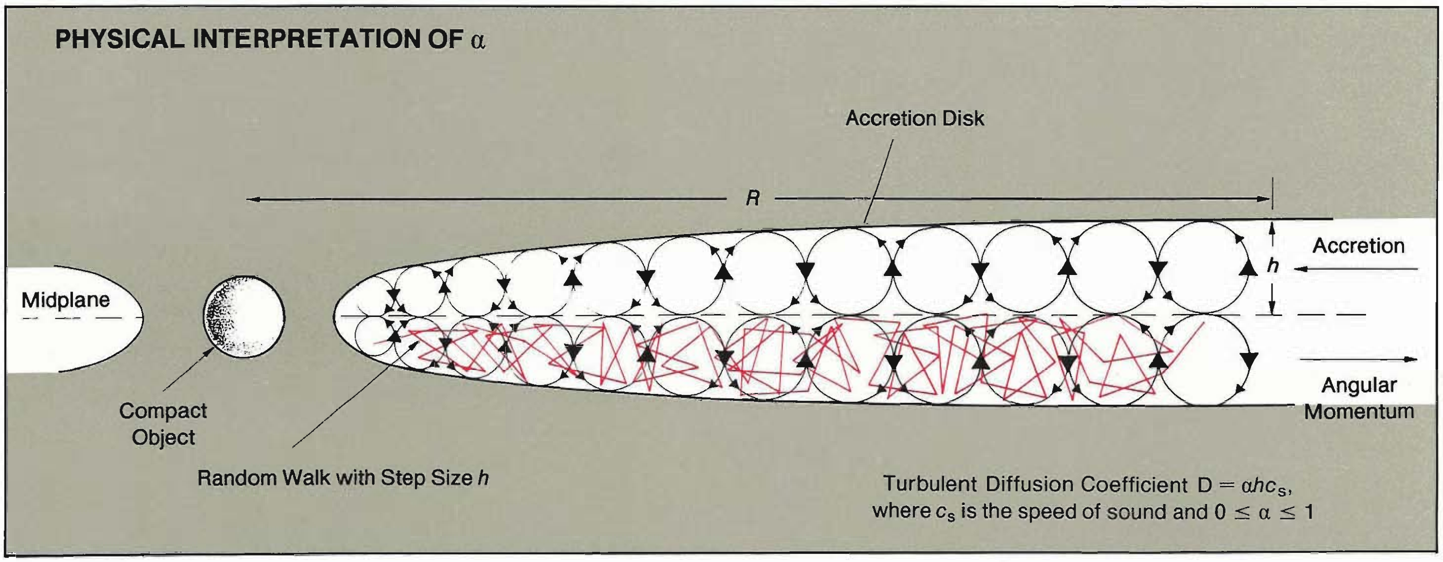

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Fig. 2. Cross section of a thin Keplerian accretion disk around a compact object. Large eddies with radii equal to the half-thickness of the disk transport angular momentum in the radial direction R. The diffusion caused by these eddies can be approximated by a random walk with step size h and velocity of the order of the sound speed c_s. Shakura and Sunyaev modeled this transport by a turbulent kinematic viscosity hc_s.

A Physical Interpretation of α. Turbulence is the enhanced transport of matter due to relatively large-scale, random motions of a fluid. If there are velocity gradients in the matter, then the effect of turbulence is to transport momentum across a mean velocity shear; it acts like viscosity or friction. The maximum rate of transport by turbulence is determined by the maximum size of the eddies; that is, the diffusion caused by turbulence can be approximated by a random walk with a step size equal to the diameter of the largest eddy. Since the largest eddy that can "fit" in the disk and transport matter in the radial direction is a round eddy whose diameter is h, the half-thickness of the disk (Fig. 2), and since the maximum velocity of such an eddy is the local sound speed c_s, the maximum possible random-walk diffusion coefficient, or turbulent kinematic viscosity D, is hc_s. Thus Shakura and Sunyaev parameterized the turbulent kinematic viscosity by αhc_s, where $0 \leq \alpha \leq 1$. To match observations α must be between 0.03 and 1.

What is the Origin of the Turbulence?

We are accustomed to the ubiquity of turbulence in fluids with velocity shears and large Reynolds numbers. Since these conditions are met in most accretion disks, it seems reasonable to expect turbulence to supply the necessary fluid friction. But, as Lord Rayleigh pointed out more than a century ago, the constraint of angular momentum conservation is strong enough to stabilize the shear flow of a Keplerian disk against shear-produced, or Helmholtz, instabilities. Hence these instabilities alone cannot drive the turbulence. Another possibility is that the turbulence is driven by heat convection. Turbulence always produces friction, but now we must ask, conversely, whether the heat produced by the friction from velocity shear is enough to drive the turbulence. In the next section we will explore this possibility as an example of how difficult it is to produce the large values of α required to transport momentum outward in Keplerian accretion disks.

Convection-Driven Turbulence. In an accretion disk, friction from velocity shears should give rise to inhomogeneous heating concentrated near the midplane of the disk. This differential heating can create instabilities that lead to turbulent motion. To transport angular momentum outward, the turbulent motion must be isotropic (or nearly so) rather than just in the "easy" azimuthal direction. It is easy to create eddies whose axes are in the radial direction and whose velocities are azimuthal, but we need an instability strong enough to overcome the stabilizing effect of angular momentum and drive radial motions. If these instabilities exist, the turbulent motion provides an effective viscosity (an "eddy" viscosity) far larger than the molecular viscosity and can transport angular momentum at the rate required for the evolution of the disk.

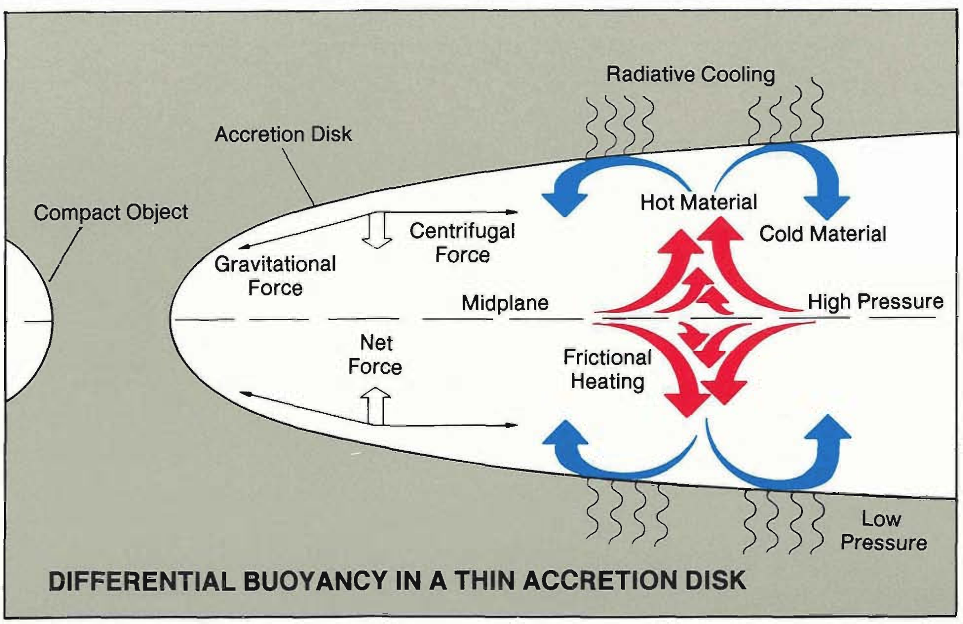
To see whether differential heating can drive the required instability, we must look at the structure of the accretion disk implied by the Shakura and Sunyaev model (see Fig. 2). As indicated above, a value of α near unity implies that the diameter of the eddies that interchange matter in the radial direction must be close to the half-thickness h of the disk, and their velocity must equal the sound speed c_s. Thus the interchange scale in the radial direction, if the eddies are round, will equal h. The internal energy in the eddy, which is determined by the sound speed c_s, will determine how much energy is available to drive the interchange. As Pringle has pointed out, the structure of Keplerian disks is such that $c_s/v = h/R$, where v is the azimuthal velocity and R is the radial distance.

The disk is densest in the midplane because the pressure is greatest there. The pressure is required to hold the material near the surface out against the component of gravity perpendicular to the disk (Fig. 3). Consequently frictional heating from velocity shears and therefore the temperature will be greatest at the midplane. The surface of the disk will be cooled by radiation. This configuration is Rayleigh-Taylor unstable in the direction perpendicular to the plane of the disk. Motions perpendicular to the disk and at the same radius do not transport angular momentum. On the other hand, motions in the radial direction do transport angular momentum and produce enhanced friction and α. The force from differential buoyancy must be large enough to create an eddy that interchanges matter over a distance $\Delta R \approx h$.

Now let's consider a single eddy and calculate how much work is needed to interchange two mass elements a distance ΔR while conserving angular momentum. We will assume an initial laminar stable state so that in the interchange of two adjacent elements of equal mass, the angular momentum of each is conserved separately (vR = constant). Then for each mass element the change in azimuthal velocity, Δv, will be such that $\Delta v/v = -\Delta R/R$. The change in specific kinetic energy of the two elements is $1/2[(v_1 + \Delta v_1)^2 - v_1^2] + 1/2[(v_1^2 + \Delta v_2)^2 - v_2^2]$. The angular momentum constraint, together with a little algebra, shows that the net change is equal to $(\Delta v)^2$. The net change in gravitational energy will be zero because we have assumed the interchange of two equal masses. Hence we need an energy equal to $(\Delta v)^2$ to effect the interchange. This energy must be provided by differential buoyancy.

The energy available from raising hot fluid and lowering cold fluid is the internal energy $E = c_s^2/(\gamma(\gamma-1))$. For a typical gas with $\gamma = 5/3$, $E \approx c_s^2$. Using the fact that $c_s/v = h/R = \Delta v/v$, we derive a maximum possible buoyancy energy of $E \approx (\Delta v)^2$. Since the work that must be done in the interchange is the same as the energy available in buoyancy, there is barely enough buoyancy to force an overturn or a circular eddy in the radial direction, especially at an eddy velocity near c_s. For the eddy to develop we need a nearly perfect heat engine that converts the heat of friction to potential and kinetic energy.

The Ideal Heat Engine. We can imagine an ideal heat engine driving the eddies. The heat is produced in our mass element of size $h = \Delta R$ at the midplane of the disk by turbulent friction due to the shear of the orbital velocity. The hot material expands adiabatically as it rises to the surface of the disk. There the remaining internal energy must be lost by radiation during the residence time of the mass element at the surface, that is, in the time $\Delta R/(\alpha c_s)$. Thus the diffusion coefficient for radiation, $(\beta c/3)(\Delta R/\tau)$, where β is the ratio of radiation energy density to total energy density $(aT^4/(aT^4 + nkT))$, c is the velocity of light, and τ is the optical depth of the disk, must be the same as the coefficient for turbulent mass transport. This implies that τ must be of order $\beta c/(3\alpha c_s)$. With these restrictions our mass element would cool, and it could then descend adiabatically with much smaller internal pressure, so less work must be done on it. When it reaches the midplane of the disk, radially displaced by ΔR, frictional heating



◀ ***Fig. 3. Accretion disks are denser at the midplane, where the gravitational potential is lower, than at points above and below it. The dense material will be heated by velocity shears and rise to the surface of the disk where it will cool by emitting radiation. The question to ask is whether the differential buoyancy is large enough to drive an eddy in the radial direction.***

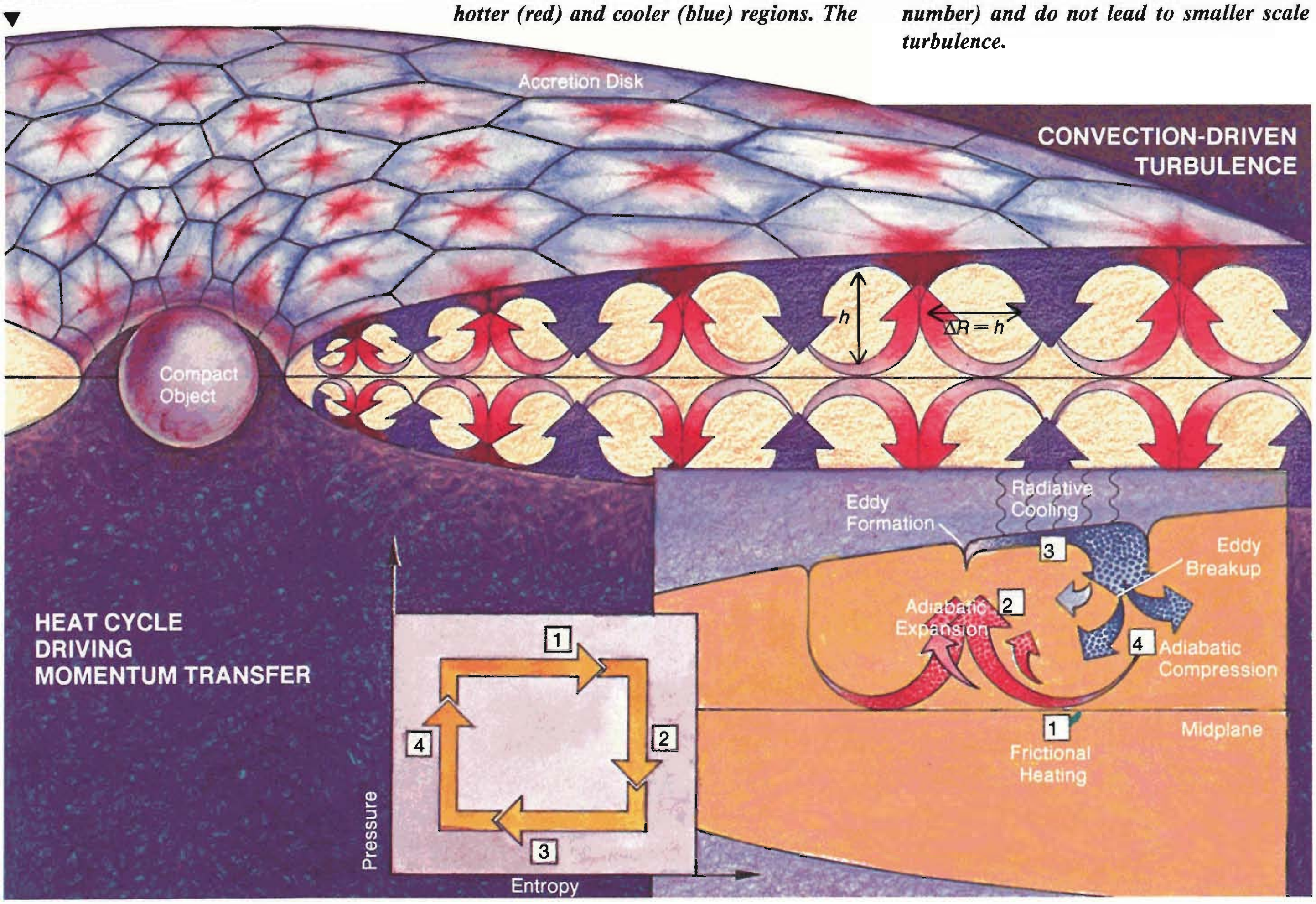
can start the cycle over again. This cycle as well as the alternating regions of hotter and cooler material that would result at the surface are illustrated in Fig. 4.

The required condition on the optical depth, together with the opacity of the material, determines the mass per unit area of the disk. Then the mass flow rate can be calculated from α and the sound speed. It is not known whether this mechanism leads to a self-adjusting disk in the sense that if the mass-injection rate changes, then α and the other parameters vary to maintain a consistent disk structure. It is also not known whether all astrophysical disks can be explained in the parameter space just outlined. Furthermore, nature does not like to make ideal heat engines, especially not in a turbulent environment because heat engines must be so perfect and turbulence is so random. Thus, the above ideal cycle, although conceptually feasible, seems difficult to justify as an explanation for the origin of α. Convection-driven turbulence does not seem strong enough to overcome the angular momentum barrier.

Thick Disks Beg the Question

The importance of angular momentum

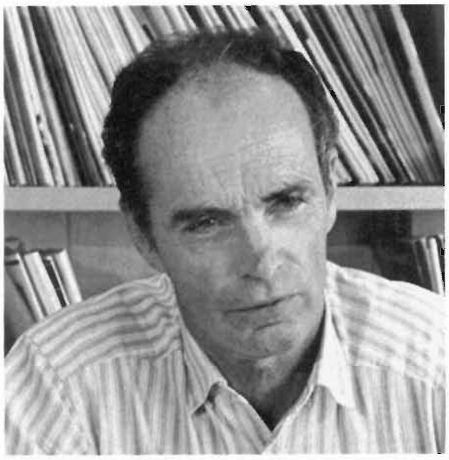
Fig. 4. Convection-driven turbulence in a thin Keplerian accretion disk creates large eddies that break the angular momentum constraint by enhancing radial transfer of angular momentum. The energy available from differential buoyancy is barely enough to drive the eddies. Their formation would require a nearly perfect engine, that is, one in which nearly all the heat was converted to work as matter flows around the eddy. The hexagonal pattern of Benard-like cells shown might be produced by heating at the midplane. The heat cycle that drives the overturn of the eddies produces alternating hotter (red) and cooler (blue) regions. The figure suggests the required breakup of the eddies into smaller scale turbulence after about half a cycle. (A persistent eddy would not produce any net transport.) This breakup is a difference between the eddies in the disk and those in a standard Benard cell, which are very slow (low Reynolds number) and do not lead to smaller scale turbulence.

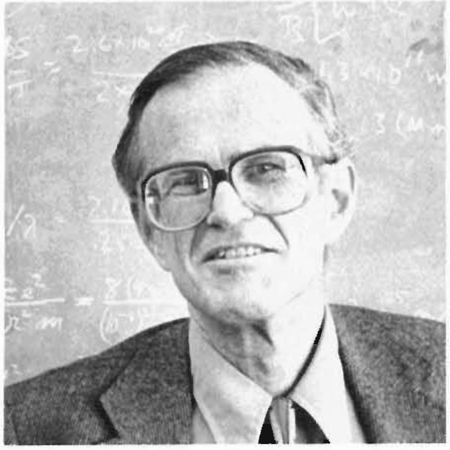


constraints is illustrated in studies of thick accretion disks by Wojciech Zurek and Willy Benz of Los Alamos. They have performed numerical simulations of the evolution of thick disks with specific angular momentum independent of radius. Because the specific angular momentum is constant, the interchange of two equal mass elements requires no energy. The disks exhibit violent Helmholtz instabilities. As one would expect, less constraint leads to greater turbulence. The instabilities cause angular momentum to redistribute itself very quickly to $J_s \propto R^q$, where q is about 0.27 (see "Redistribution of Angular Momentum in Thick Disks"). Thus the disk becomes more Keplerian, but since these instabilities are damped the disk never becomes truly Keplerian ($q = 0.5$).

Such models invite the question of how a disk can be formed with small and nearly uniform angular momentum. In the case of quasars and active galactic nuclei powered by the accretion of matter onto massive black holes, these disks might be formed by the gravitational breakup of stars scattered by interactions with other stars in the strong gravitational field close to the massive black hole. More specifically, stars in a dense galactic nucleus scatter at random. Occasionally one of these scattering events causes a star to approach the black hole with an impact parameter so small (several Schwartzschild radii) that the star deforms tidally and a fraction of the star is captured. Other stars of the cluster then have a slightly greater angular momentum because of its conservation. Jack Hills of Los Alamos calculated that a thick disk of low angular momentum is a reasonable outcome of such accretion.

Thus there may not be an angular momentum problem in feeding a black hole, but the original problem of making a star from tenuous gas remains. Either we must posit an initial gaseous state of tiny and thus statistically unlikely angular momentum, or we are left with the imperative to find a transport mechanism for the cosmic pollutant. ■





AUTHORS

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Beta Pictoris. A color-coded map created from optical images of Beta Pictoris and the similar star Alpha Pictoris, both taken with a coronagraph and a charge-coupled device at the Las Campanas Observatory in Chile. The disk surrounding Beta Pictoris was revealed by plotting the ratio of the intensity of scattered light around Beta Pictoris to that around Alpha Pictoris. Reproduced with permission of Bradford A. Smith, University of Arizona, and Richard J. Terrile, Jet Propulsion Laboratory.

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M81. A color-enhanced image in which radiation from gas in the spiral arms of the galaxy appears blue and radiation from older stars in the disk appears orange. The image was composed from single-color photographs taken with Palomar Observatory's 48-inch Schmidt telescope.© Halton C. Arp; reproduced with permission.

Rings of Saturn. An optical image in real color created from data collected in October 1980 by NASA's Voyager I satellite. The rings have been enhanced with additional color. Reproduced with permission of the NASA Jet Propulsion Laboratory.

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Redistribution of Angular Momentum in Thick Accretion Disks

by Wojciech H. Zurek and Willy Benz

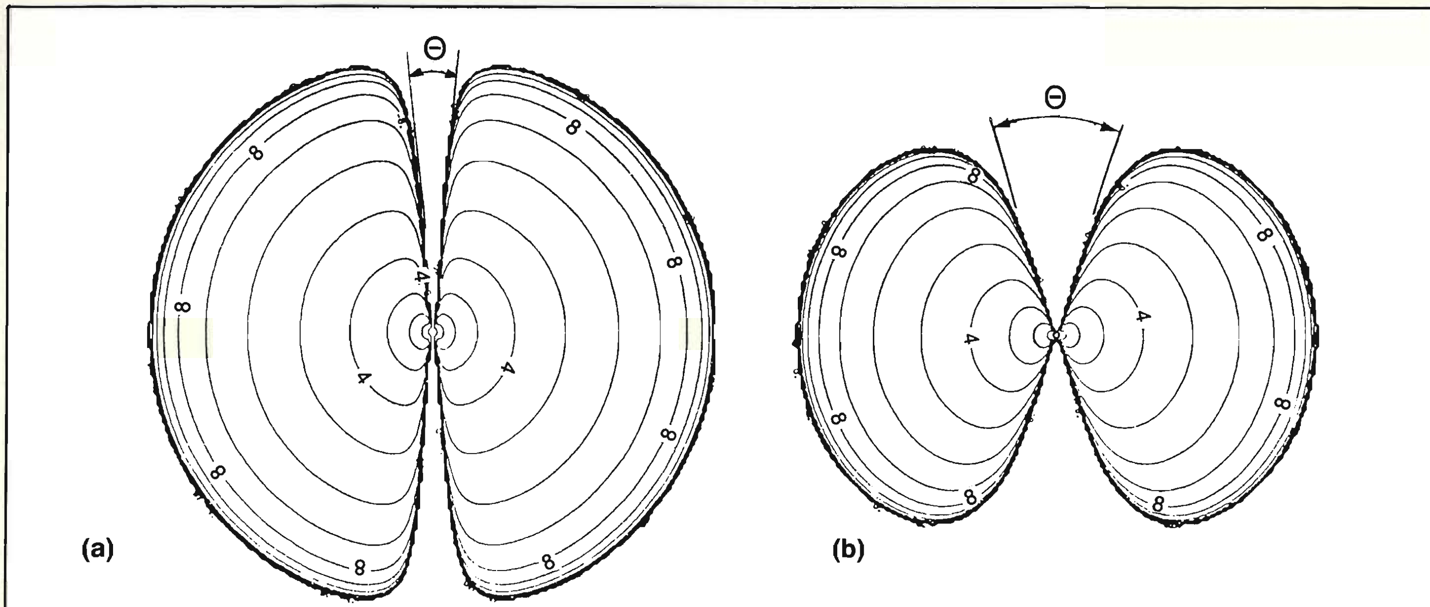

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Fig. 1. Isodensity contours of two tori with approximately the same inner and outer radii, but with different distributions of specific angular momentum: (a) a torus with J_s = constant and (b) a torus with $J_s \sim r^{0.27}$ Note the change in the funnel opening angle from ~10° in (a) to ~30° in (b). The density decreases by twelve orders of magnitude from the innermost to the outermost contours.

The importance of the distribution of angular momentum is illustrated in our recent numerical simulations of thick accretion disks. These torus-like disks, in contrast to the flat, pancake-like Keplerian disks, have a height above the equatorial plane comparable to their extent in the radial direction. Until recently the constant specific angular momentum ($J_s \approx$ constant) variety of such non-Keplerian accretion disks around massive black holes was considered the best model for the central "powerhouse" in quasars and active galactic nuclei. However, doubts about the validity of that hypothesis were raised in 1984 by analyses of the stability of the disks by Papaloizou and Pringle. Our numerical simulations confirm those first suspicions. More important, we were able to demonstrate that growing instabilities in a constant-J_s torus rapidly redistribute angular momentum, causing the torus to become thinner and more Keplerian. Hence thick accretion disks with constant J_s cannot be regarded as models for astrophysical objects.

The equilibrium configuration of thick accretion disks, for constant J_s and large pressure forces (sound speeds comparable to rotational velocities), looks like a fat torus, or doughnut (Fig. 1a). The sides of the torus form a funnel, with a small opening angle θ, about the rotation axis. As noticed by Lynden-Bell, this is a perfect shape for a deLaval nozzle,* that is, for accelerating the enormous supersonic jets observed to be emanating from so many active galactic nuclei. Moreover, the steep walls of the funnel allow the luminosity of the torus to exceed the Eddington limit, a property that would be indeed useful in modeling variable quasars with huge power outputs.

The first question to ask is how such non-Keplerian accretion disks can exist, since matter at small radial distances r has "too much" angular momentum (more than the Keplerian value) and matter at large r has "too little" angular momentum. The pressure in the disk is responsible for maintaining this distribution of angular momentum: the matter at large r is being prevented from moving inward by the pressure, and the matter at small r is being kept from moving outward by the pressure-mediated weight of the outer parts of the disk.

Proponents of $J_s \approx$ constant accretion disks assume that the effective turbulent viscosity of such a disk is very small, so that it is all but impossible to transport angular momentum outward as matter accretes toward the massive body at the center of the disk. However, if the central massive body is a black hole (as it is almost certain to be for quasars and active galactic nuclei, including the nucleus at the center of our own Milky Way), then it is possible to get rid of the angular momentum of accreting matter by pushing it into the black hole. The necessary push can be provided by applying pressure from far away and "force-feeding" the black hole with gas.

Using an idealized model, Papaloizou and Pringle challenged the foundations of the thick accretion disk theory by showing that constant-J_s tori are violently unstable against nonaxisymmetric shear-driven perturbations. The instabilities revealed by their linear analysis are Helmholtz instabilities and in some ways are analogous to "fire-hose" instabilities. However, the gas does not stream out in random directions, as would water from a hose left unattended. Instead the gas deflected from its equilibrium orbit by the instability is bound by the gravitational potential and so produces density inhomogeneities, pressure gradients, and sound waves, which, in turn, produce more deflections, which lead to more sound waves.

In a second paper Papaloizou and Pringle extended the stability analysis to include very thin tori (like slender bicycle tires) with J_s varying as r^q. For $q < 2 - \sqrt{3} \cong 0.2679$, the tori were found to be unstable. For greater values of q a large class of unstable modes is stabilized. Their linear analysis did not, however, reveal the ultimate fate of the original configuration.

**The action of a deLaval nozzle is described by M. L. Norman and K.-H. A. Winkler in "Supersonic Jets,"* Los Alamos Science *Number 12, 1985.*

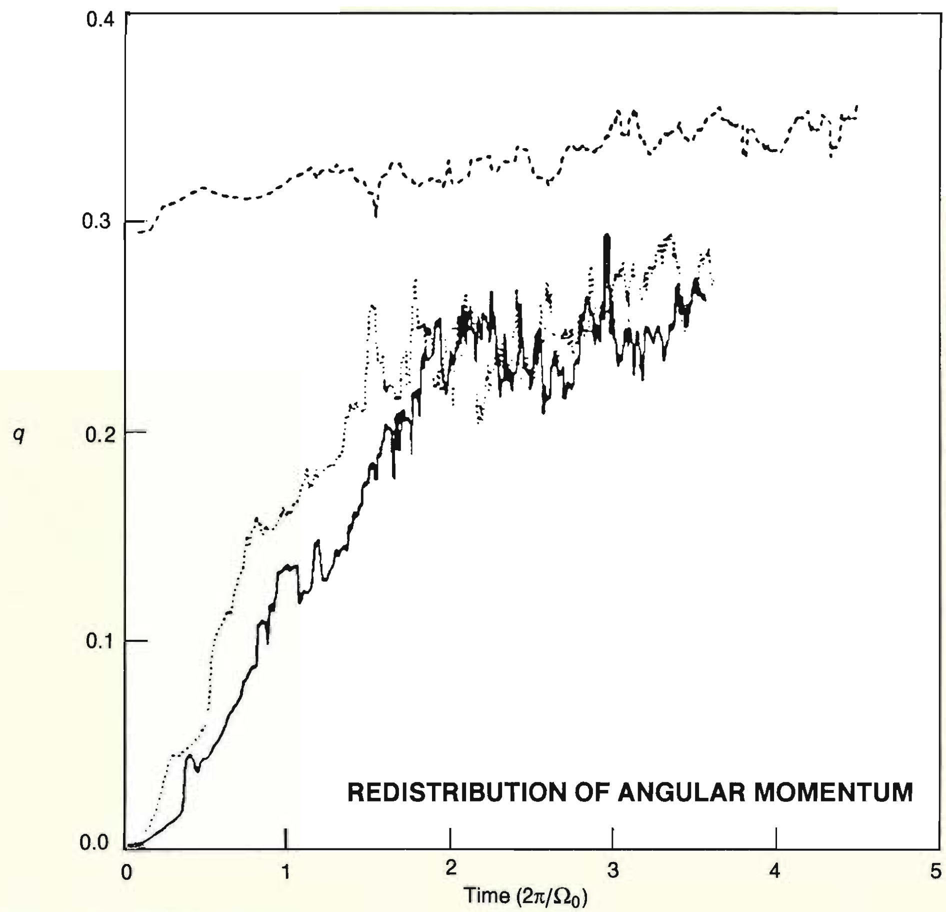
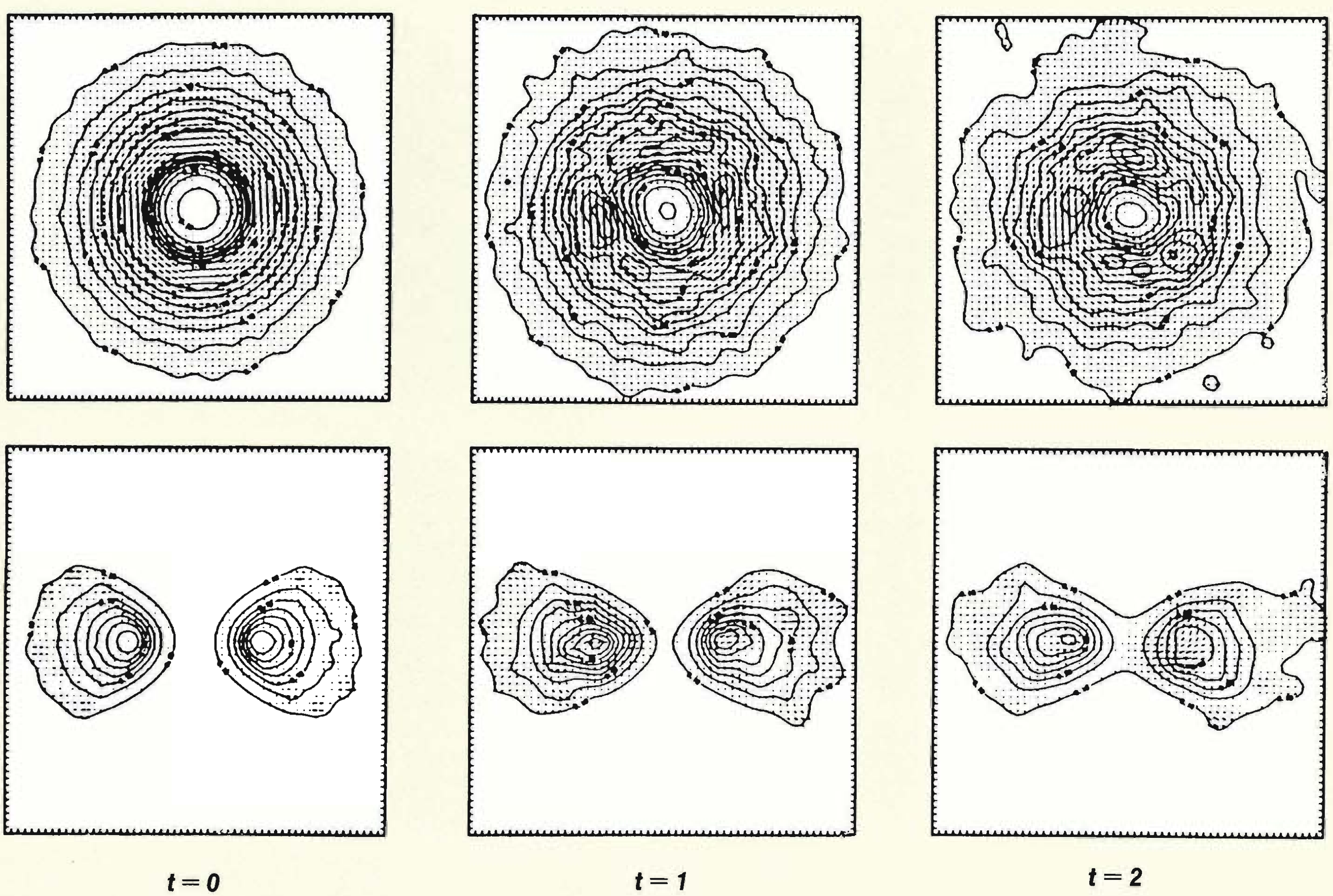


Fig. 2. The exponent q as a function of time, where q is calculated from a power-law fit ($J_s \sim r^q$) to the specific angular momentum distribution obtained from the numerical simulation. The results are shown for three simulations. Note that, for the two disks with initially constant specific angular momentum, q increases rapidly from 0 to about 0.27 within about two rotation periods. After the critical q $= q_c \sim 0.27$ is reached, the redistribution of angular momentum slows down to the rate observed in a disk with initial $J_s \sim r^{0.3}$. It is not yet known whether this slow rate of angular momentum transport is caused in part by nonaxisymmetric instabilities or is totally explained by a numerical viscosity that is an unavoidable artifact of such calculations. We are planning to study this problem further.

We have extended such stability analyses to the nonlinear regime by adding a small random density perturbation (of the order of 1 percent) to an initial equilibrium configuration with constant J_s (see Fig. 3, $t = 0$). These numerical experiments not only confirm that such disks are unstable but also show that a fat accretion torus is forced to undergo a "crash diet": instabilities redistribute the angular momentum very quickly (on the time scale of about a rotation period !) from J_s = constant to $J_s \sim r^{q_c}$, where q_c turns out invariably to be 0.27 (Fig. 2). Note that this value for the

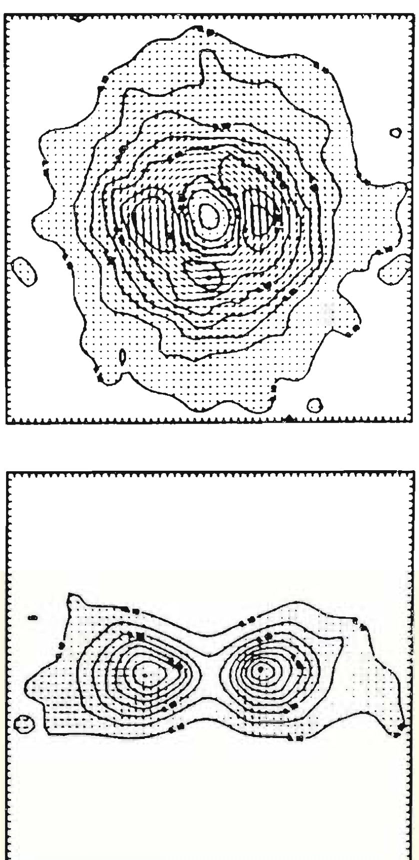
Fig. 3. A computer-generated time sequence showing the three-dimensional evolution of the central region of a thick accretion disk with initially constant specific angular momentum. The upper panels show isodensity contours in the equatorial plane of the central region; the lower panels show isodensity contours in a plane parallel to the rotation axis. The density decreases by one to two orders of magnitude over the region shown. Time is expressed in rotation periods of the density maximum. The velocity field is indicated by means of arrows whose lengths are normalized to the maximum value of the velocity in each frame. Following the introduction of a small nonaxisymmetric perturbation, the growth of instabilities causes a rapid redistribution of angular momentum that, in turn, flattens the disk and fills in the central "hole." This simulation was made with a three-dimensional hydrodynamics code that uses the so-called smoothed particle hydrodynamics method (Lucy 1977). This free Lagrangian approach to solving the usual equations of hydrodynamics replaces the continuum by a finite set of spatially extended particles. Thus no mesh is required, and the usual problems as-

TIME EVOLUTION OF A THICK DISK



exponent is about the same as that obtained by Papaloizou and Pringle for the stabilization of "bicycle tire" tori. Figure 3 shows the time evolution of the disk.

sociated with its rezoning are bypassed. The simulation is made by computing the trajectories of 1000 extended particles that interact through pressure forces in a central gravitational potential. Since the particles are allowed to move without any constraints in all three spatial directions and since a mesh is not needed, this method is particularly suited for the simulation of highly distorted flows.



***t* = 3**

As the angular momentum is redistributed, the fat torus becomes much thinner and much more Keplerian in appearance. Moreover, the narrow funnel invoked to explain the formation and collimation of relativistic jets becomes much wider (Fig. 1b) and therefore less effective in producing collimated jets and super-Eddington luminosities.

Regarding the question of angular momentum transport discussed in the main text, our calculations show that, at least for $q < q_c$, shear-driven instabilities provide a powerful source of the "rub," that is, of α, the turbulent viscosity. The next obvious question—not addressed properly by the calculations performed to date—is whether the shear-driven instabilities will provide a mechanism for α when $q > q_c$. Can these instabilities generate wave-like excitations and "interesting" α values in disks that are "barely" stable ($J_s \approx r^{q_c}$) or almost Keplerian ($J_s \approx r^{0.5}$)? We are now exploring this question with one of the new three-dimensional hydrodynamics codes developed at Los Alamos. ■

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