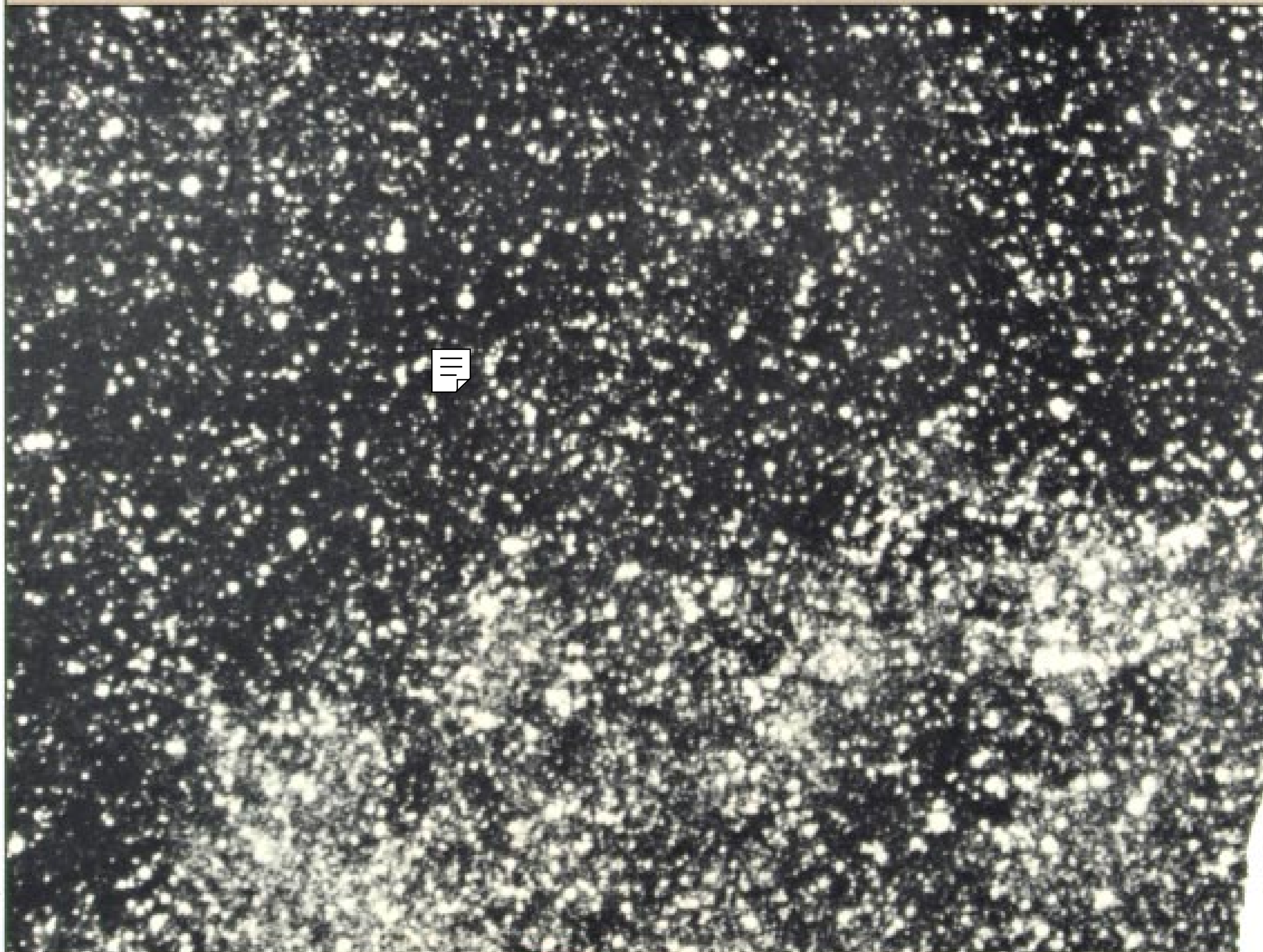
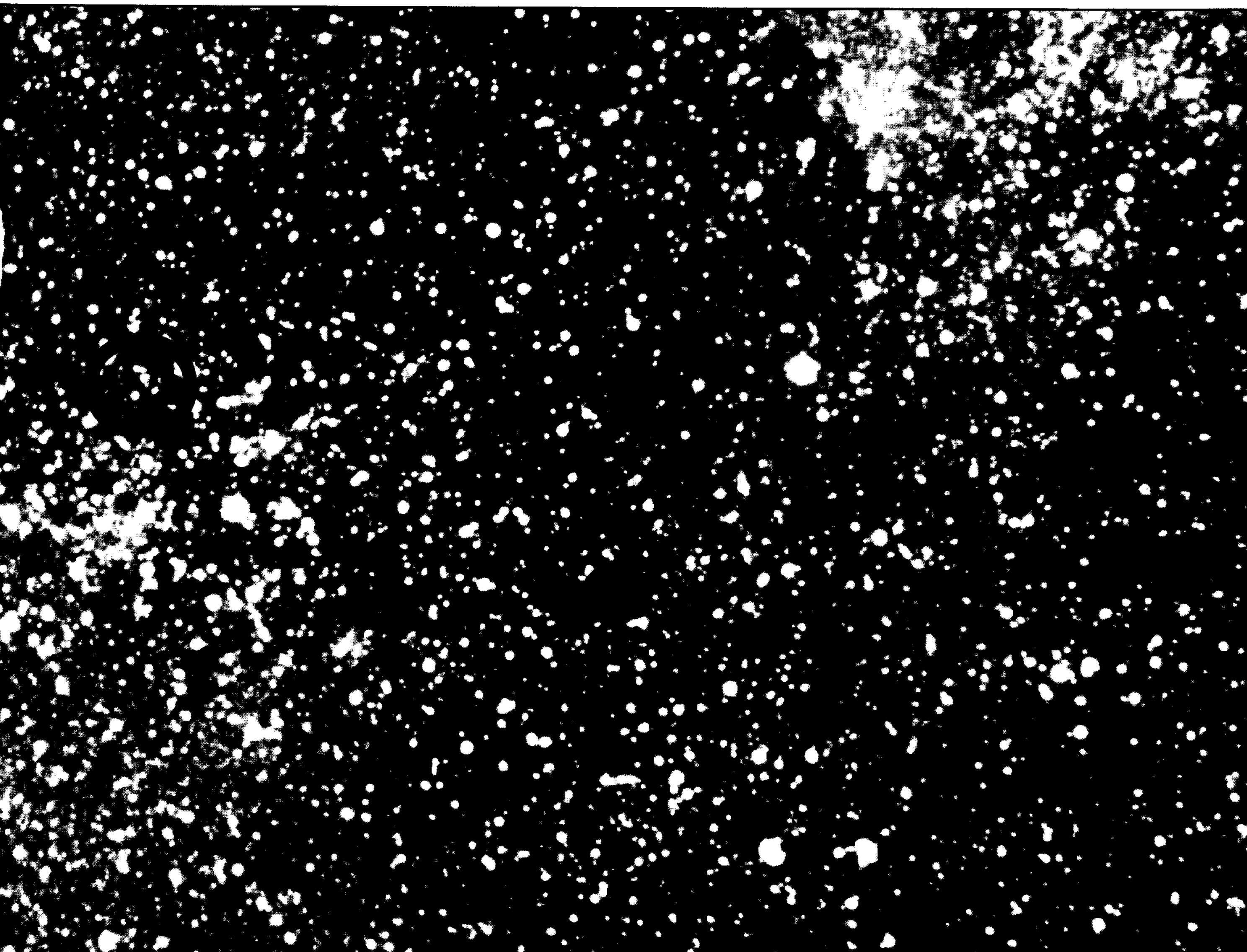
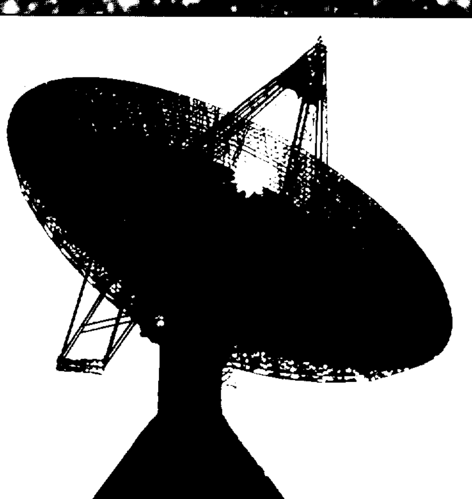


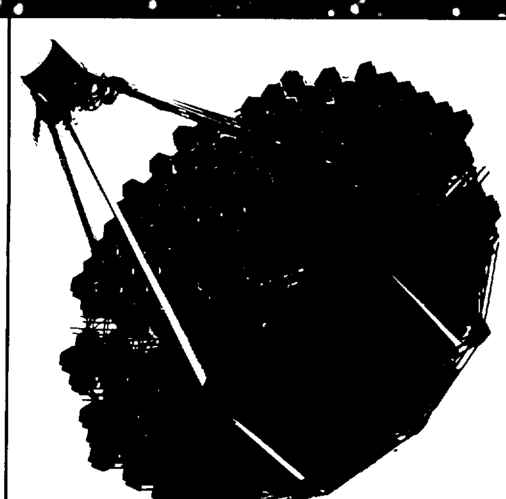
Photo by Dennis di Cicco

CYGNUS X-3

And The Case For Simultaneous Multifrequency Observations







by France Anne-Dominic Cordova

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 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 multi frequency 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* multi frequency observations. In the past few years groups of astronomers, some including as many as

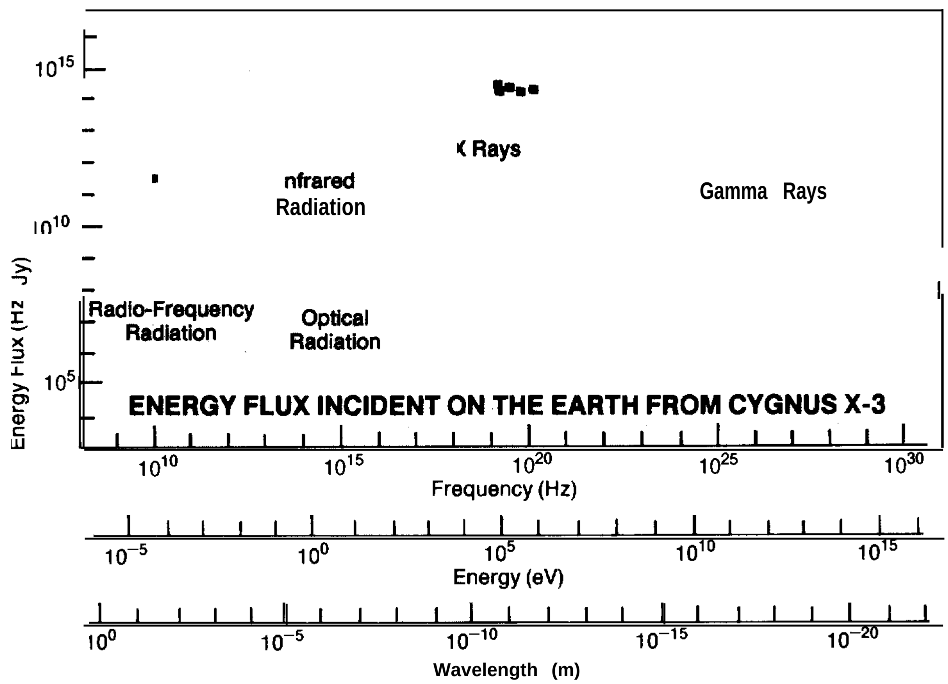


Fig. 1. The energy flux at the earth due to electromagnetic radiation from Cygnus X-3 as a function of the frequency and, equivalently, energy and wavelength of the radiation. The data points in white are typical values for this variable source during quiet states, those in gray are values obtained during 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}.)

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 nonsimultaneous 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 Mayan 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 Mayan 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. ■

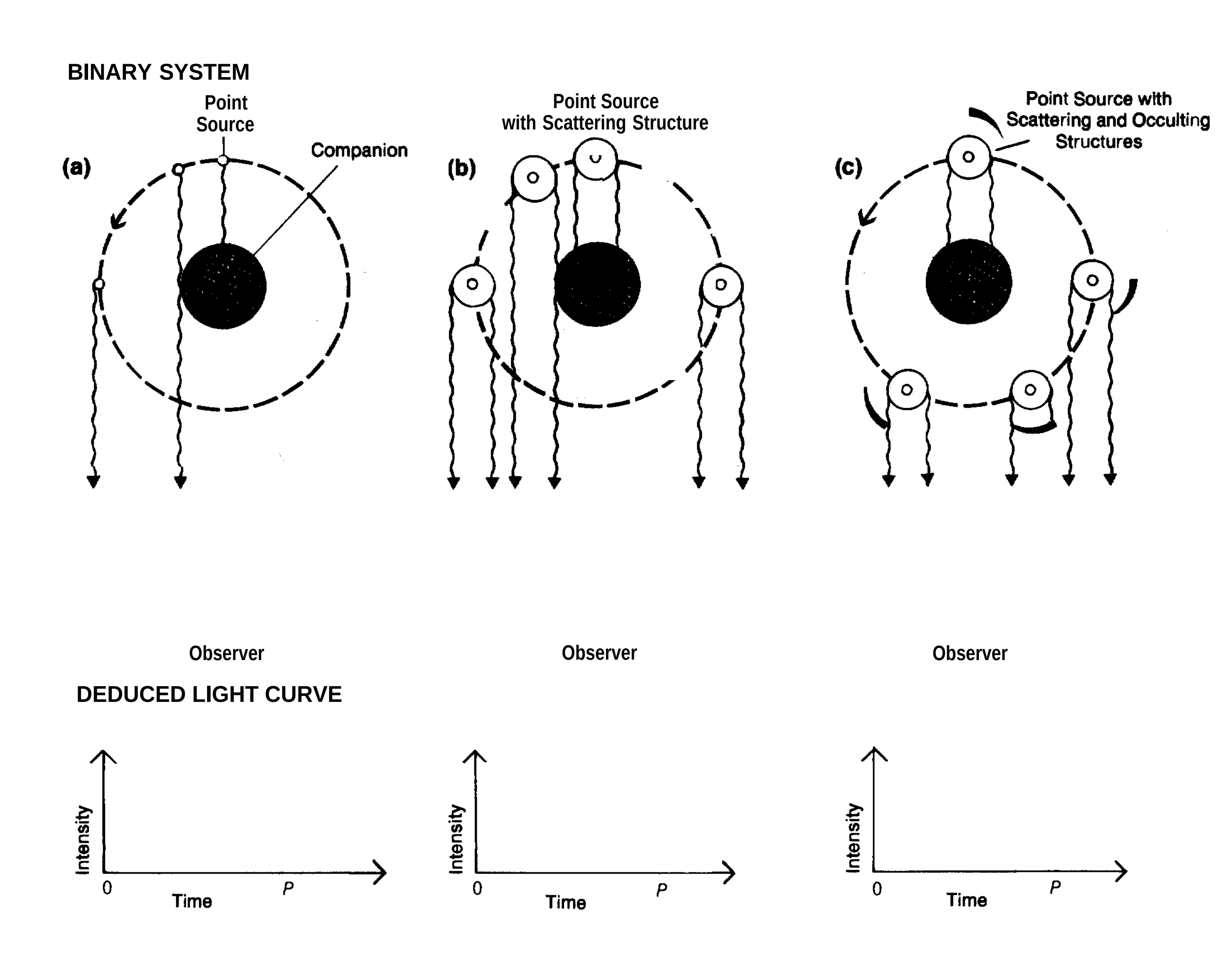


Fig. 2. Modulation by orbital motion of the intensity of radiation from a binary system. (a) Consider a binary system consisting of a pointlike, nonvariable source of radiation and a larger, nonradiating, opaque, spherical companion rotating about each other in a circular orbit. (The system is shown 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 = O 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.

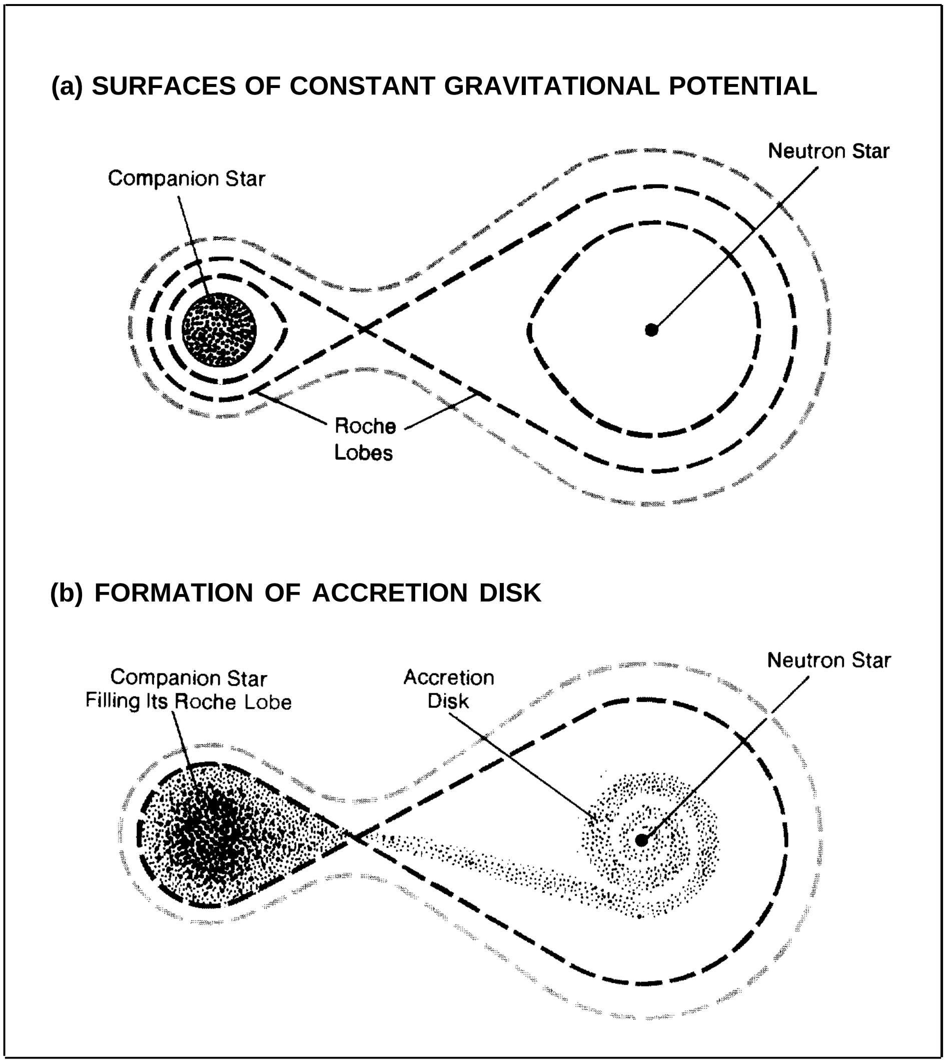


Fig. 3. The gravitational potential in the vicinity of a binary system can be visualized by means of surfaces on which the gravitational potential is constant. Shown in (a) are cross sections (through the orbital plane) of three such equipotential surfaces for a binary system composed of a neutron star 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 earned 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

X-RAY LIGHT CURVE OF CYGNUS X-3

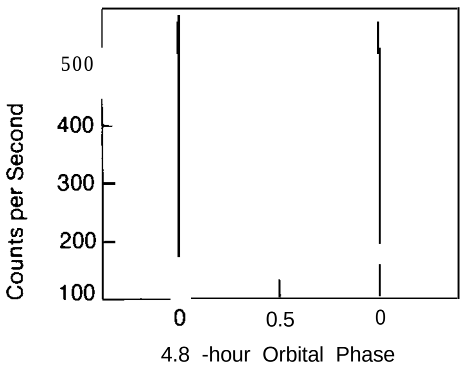


Fig. 4. This sketch of the x-ray light curve of Cygnus X-3 is based on EXOSAT data taken in September 1984 by the author, K. O. Mason, and N. E. White. Note the broad dip to the minimum intensity, the asymmetry of the dip about the minimum, and the large and rapid variations in intensity outside the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

from 1 to 150 keV during numerous balloon- and satellite-mounted experiments (1 keV = 1000 electron volts ≃ 2.4 X 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 1037 to 10^{38} ergs per second. (For comparison, the sun's total luminosity is 4 X 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 beam-like 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-

FREQUENCY DEPENDENCE OF RADIO BURST

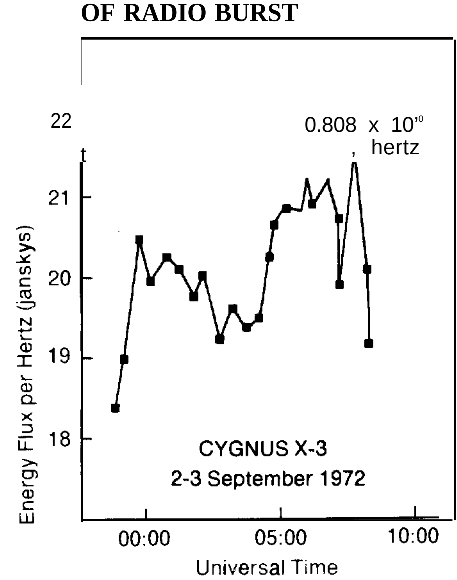


Fig. 5. The initial stages of the first detected radio-frequency burst from Cygnus X-3 were observed at two frequencies. Note that the maximum energy flux per hertz attained is greater at the higher frequency, and that the maximum at the lower frequency occurred later in time. These features have been 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.)***

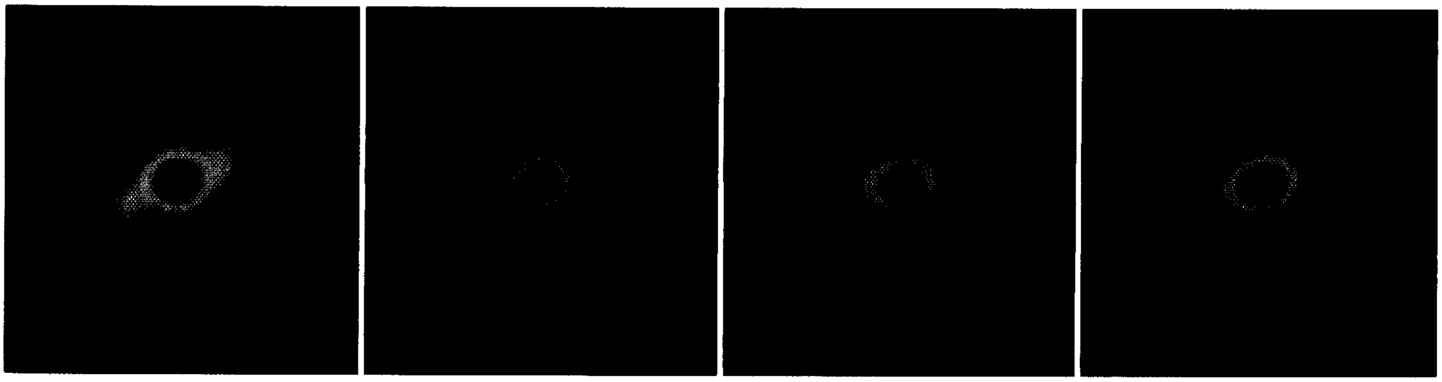


Fig. 6. A chronological sequence of color-coded radio-frequency intensity maps of the binary system SS 433 obtained with the VLA during the first four months of 1981. The low-intensity (blue) regions moving outward from the source are interpreted as synchrotrons radiation emitted by relativistic electrons 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 synchrotrons 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

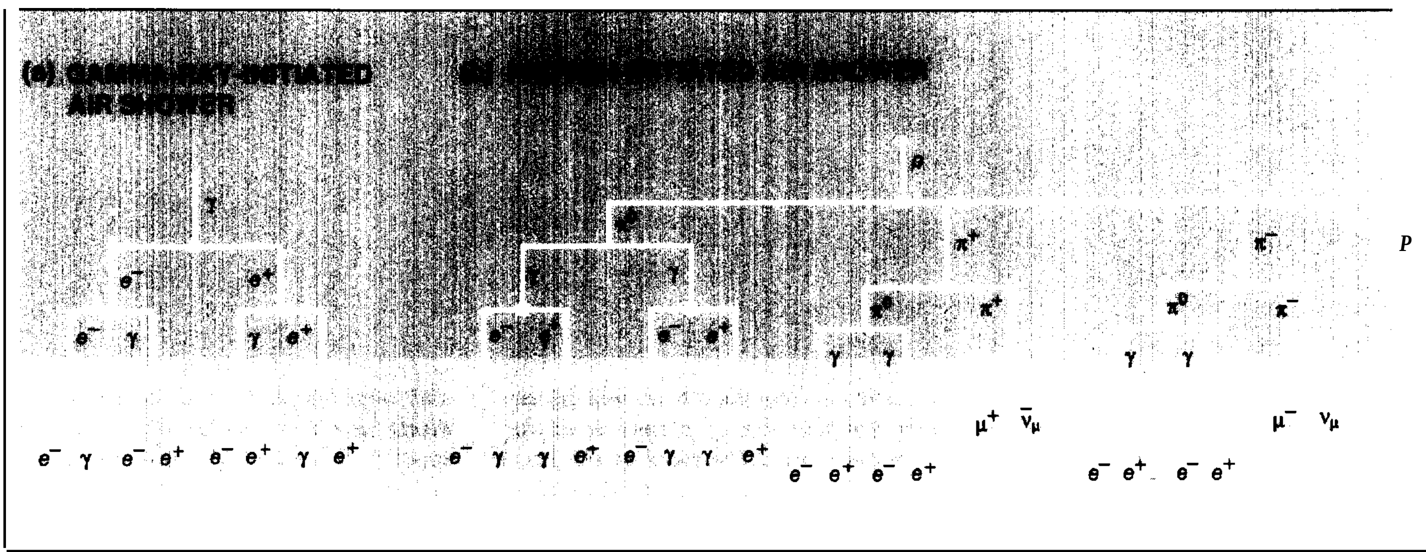


Fig. 7. Examples of air showers initiated in the earth's atmosphere by energetic radiation (photons or particles) from astronomical sources. Such an air shower consists of an increasingly numerous assortment of secondary photons and particles advancing together in a plane perpendicular to the direction 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 Cerenkov 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 Cerenkov 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

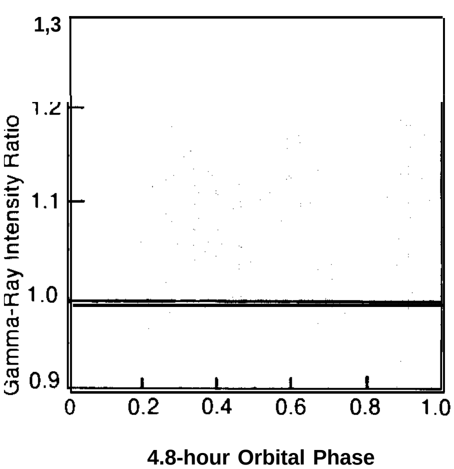


Fig. 8. This light curve is based on detection of Cerenkov radiation emitted by secondary particles in air showers. The energies of the primary gamma rays are greater than about 1 TeV. The ordinate is the ratio of the Cerenkov radiation intensity with the source inside the field of view to that with 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 Cerenkov 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 perio-

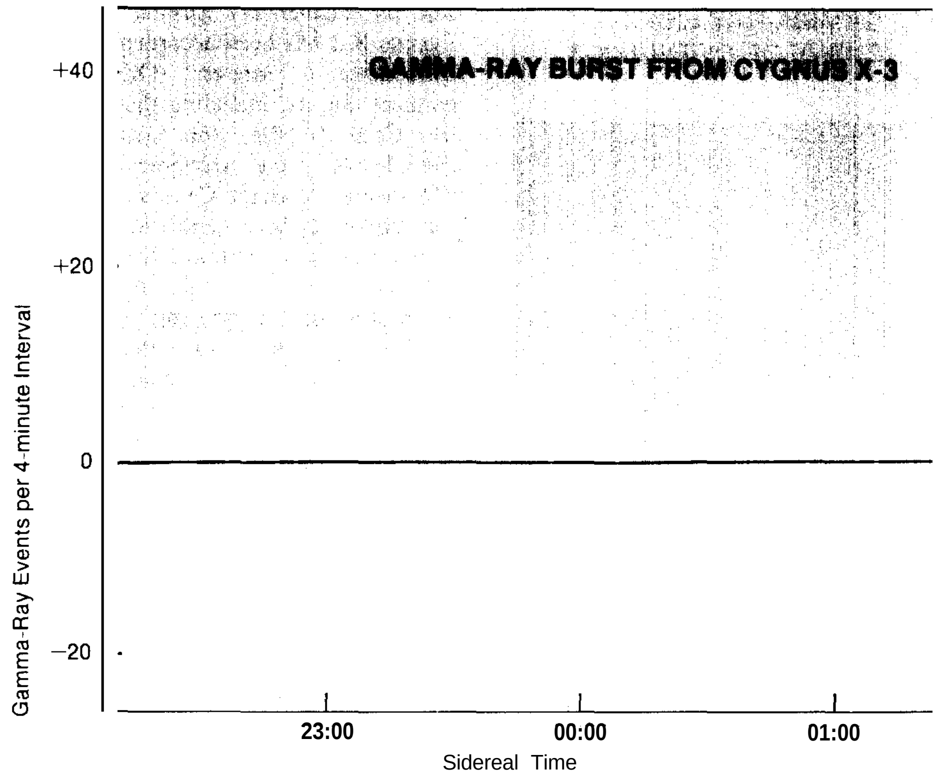


Fig. 9. Cygnus X-3 is an intrinsically variable gamma-ray source, as demonstrated by this plot of an 8-minute burst. The energies of the primary gamma rays are greater than about 1 TeV. (Figure adapted from T. C. Weekes, Astronomy and Astrophysics *121(1983):232.)*

dicity 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.

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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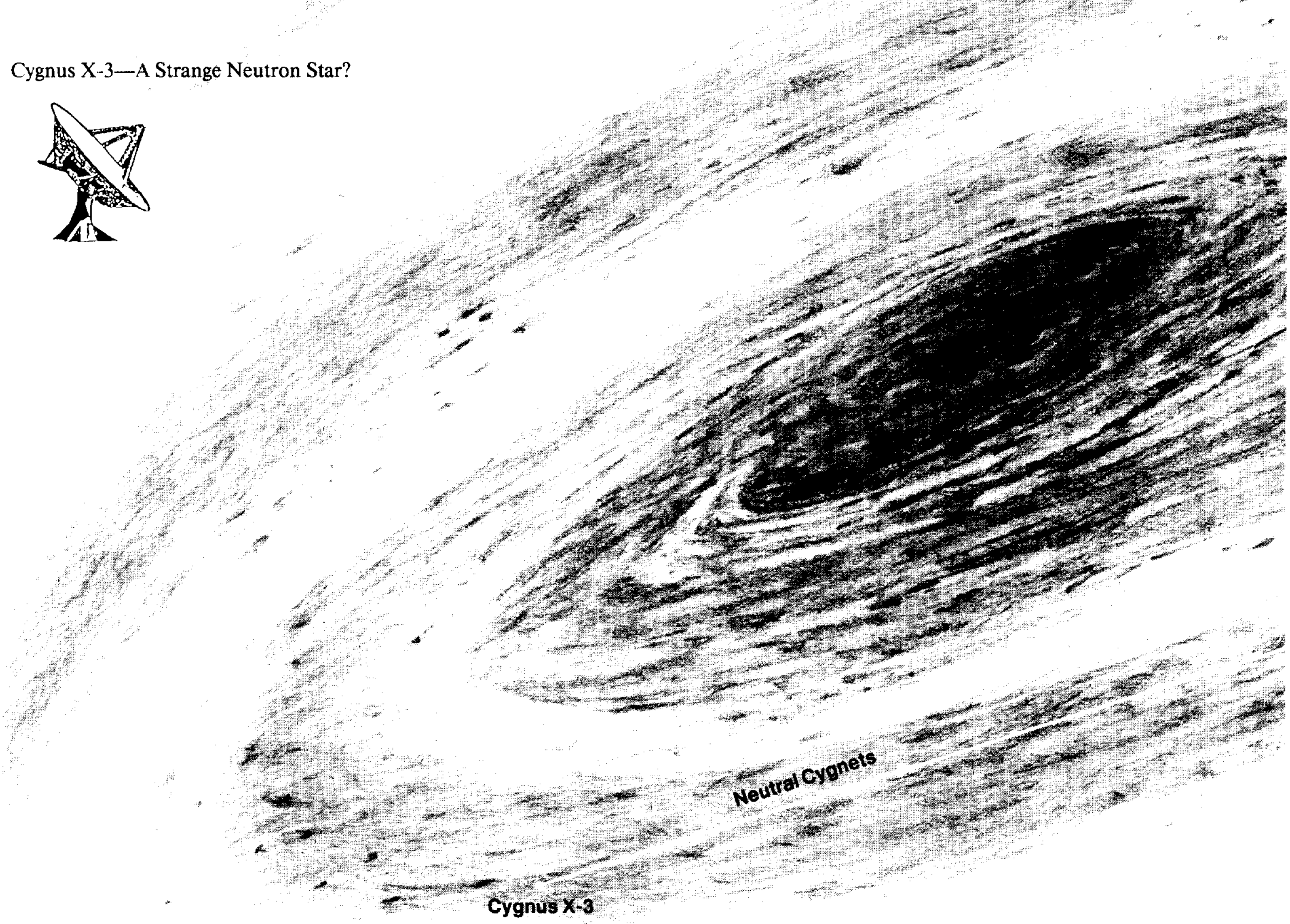

Deep underground proton-decay detectors in the Soudan iron mine in Minnesota and under the Mont Blanc have recorded very energetic muons coming from the direction of Cygnus X-3 with its 4.79-hour periodicity. These observations, if confirmed, present a very challenging puzzle. What is the primary cosmic-ray 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 1OO-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

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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 His thus a particle with a strangeness 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 (1.1 16 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

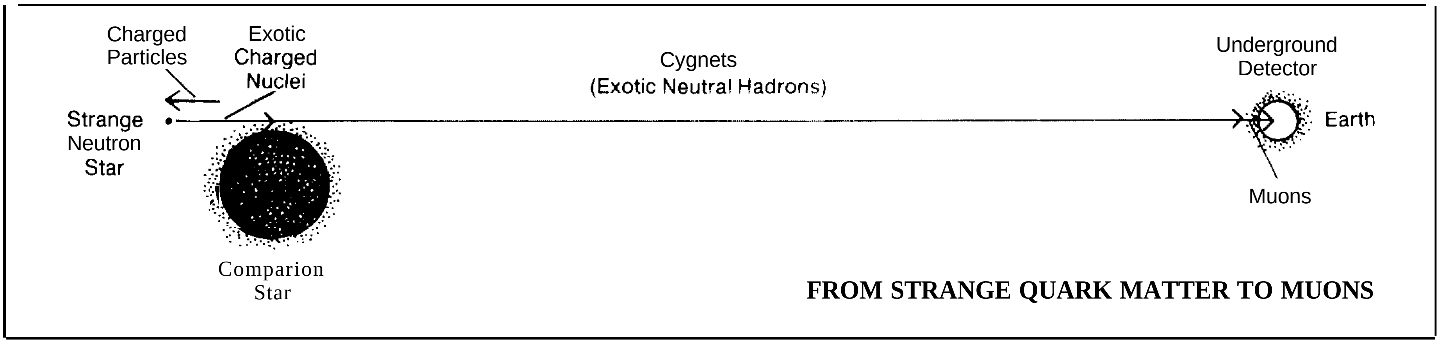


Fig. 1. A scenario for the observation, in underground detectors, of muons with the directionality and periodicity of Cygnus X-3. Particles accelerated onto the surface of a strange neutron star cause ejection of exotic charged nuclei, which are accelerated outward and fragment as they pass through the 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.

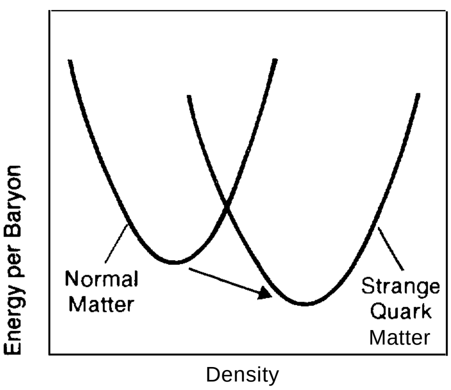


Fig. 2. If, as illustrated here, the minimum in the energy per baryon versus density curve for normal nuclear matter is higher than that for strange quark matter, then normal matter, which in its ground state sits at the minimum of the normal matter curve, would be unstable against transition to strange 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 X 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 sugest 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. ■

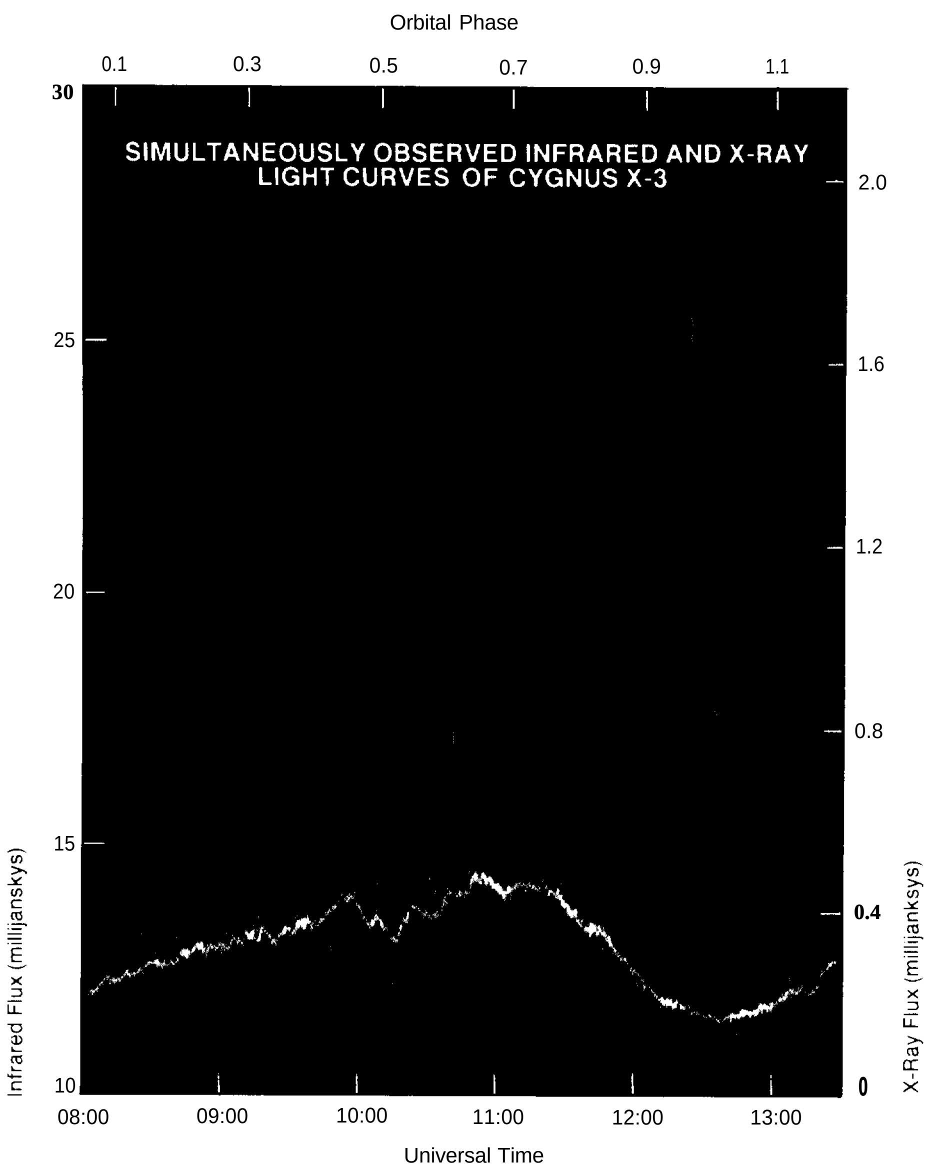


Fig. 11. Simultaneous infrared (red) and x-ray (blue) data taken by the author and K. O. Mason on 2 September 1984 are plotted here with the infrared and x-ray minima superposed to emphasize the almost identical shapes of the orbital modulations. The flares so evident in the infrared data have no apparent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

continued from page 49
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 multifrequency 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 co]-leagues, 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 Cordova

The galactic x-ray source known by its coordinates as X 1822—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 X 1822–371 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 Xl 822–371 could be interpreted as resulting from Comptonization of a hard x-ray spectrum by an optically thick corona.

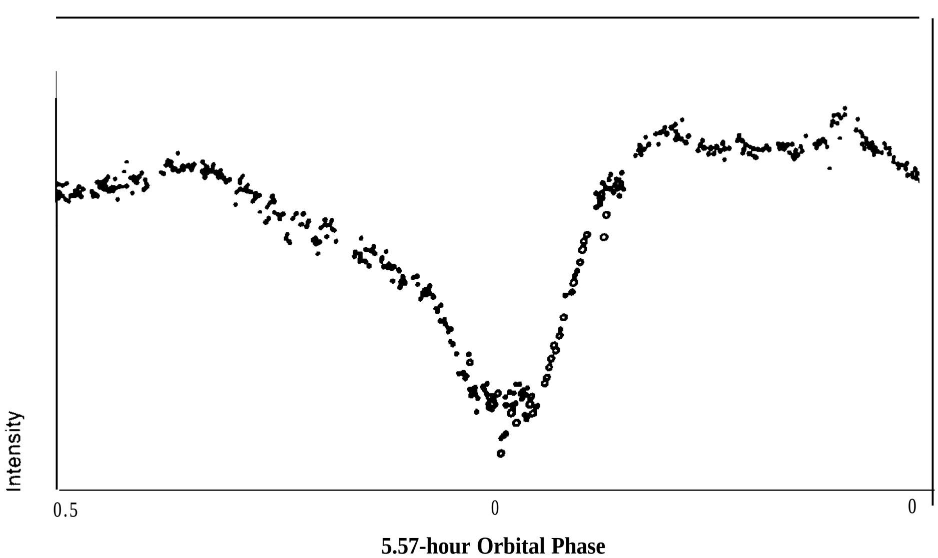
White and Holt showed how the broad dip in the x-ray light curve could arise from occultation of the corona by a prominent bulge on the outer edge of the accretion disk at the confluence of the disk and the stream of accreting matter. This bulge may be caused by turbulence. A smaller

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

OPTICAL LIGHT CURVE OF X1822--371



X-RAY LIGHT CURVE OF X1822–371

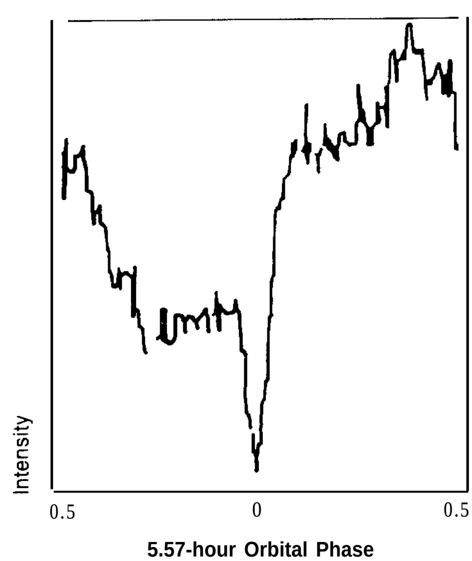


Fig. 1. Both the optical and the x-ray light curves of X1822—371 show a narrow dip to the minimum intensity convoluted with an earlier, broader dip. Both curves can be reproduced with the accretion-disk corona model (see text). (Optical light curve adapted from K. O. Mason, J. Middleditch, J. E. Nelson, N. E. White, P. Seitzer, I. R. Tuohy, and L. K. Hunt, The Astrophysical Journal *242(198O):L1O9. X-ray light curve adapted from N. White and K. Mason,* Space Science Reviews *40(1985):167.)*

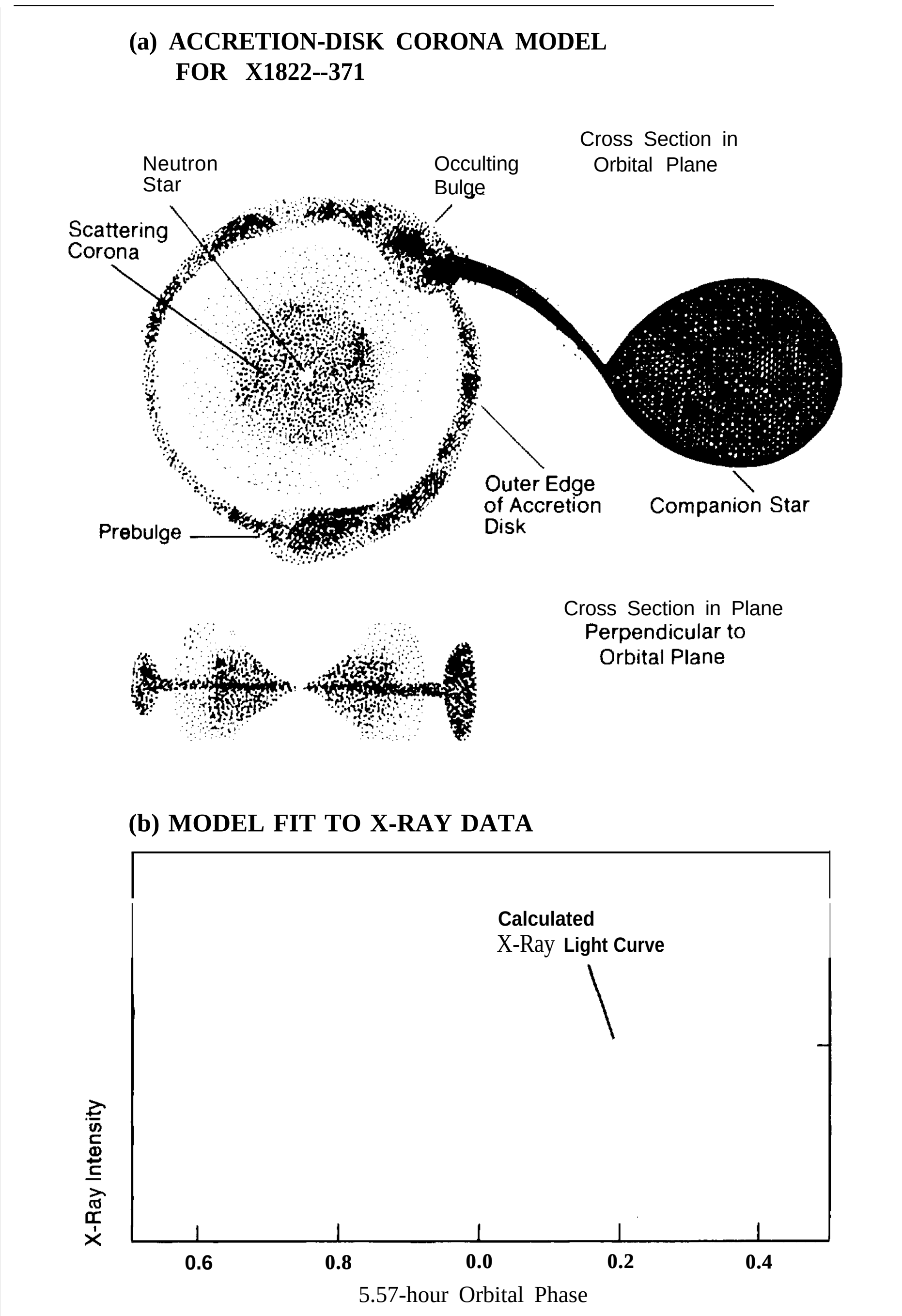


Fig. 2. An accretion-disk corona model for X1822–371 containing the structural features shown in (a), namely, a scattering corona within the disk and occulting bulges on the outer rim of the disk, can befitted, as shown in (b), to the x-ray light curve with appropriate choices for the geometric parameters 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 tits to the three light curves were obtained with a binary inclination of about 80°. Their tit 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 X 1822–371 (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

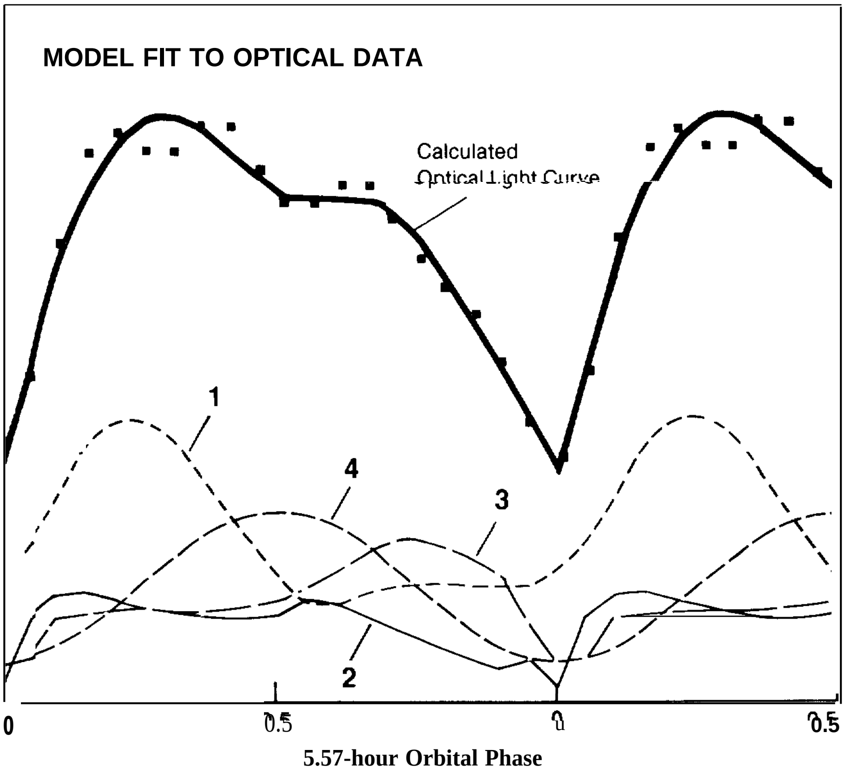


Fig. 3. If the optical radiation from X1822–371 is assumed to consist of a weighted sum of contributions from four luminous regions, its optical light curve can be reproduced well by the accretion-disk corona model. The luminous regions are (1) the inner surface of the thickened rim of the accretion 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. Cordova, 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. ■

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