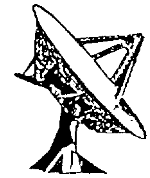


X1822 – 371 and the Accretion-Disk Corona Model

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.

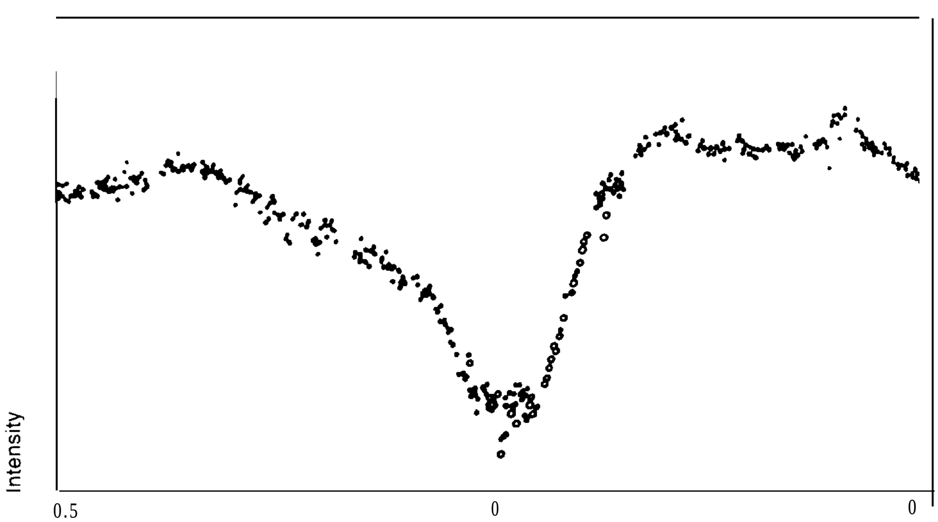
White and Holt showed how the broad dip in the x-ray light curve could arise from occultation of the corona by a prominent bulge on the outer edge of the accretion disk at the confluence of the disk and the stream of accreting matter. This bulge may be caused by turbulence. A smaller

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	$0.5 R_\odot$ 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 Cordova 1982
Distance	2 to 3 kiloparsecs	Mason and Cordova 1982

OPTICAL LIGHT CURVE OF X1822--371



X-RAY LIGHT CURVE OF X1822–371

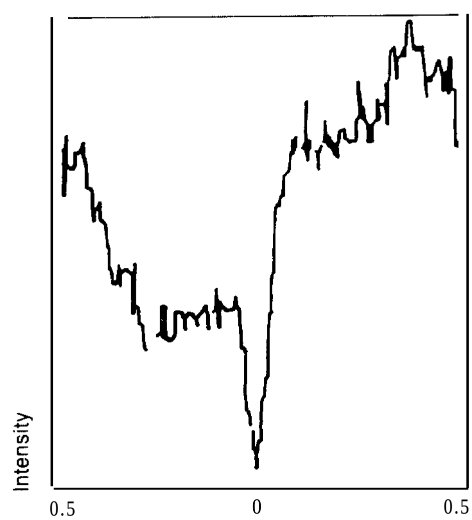


Fig. 1. Both the optical and the x-ray light curves of X1822—371 show a narrow dip to the minimum intensity convoluted with an earlier, broader dip. Both curves can be reproduced with the accretion-disk corona model (see text). (Optical light curve adapted from K. O. Mason, J. Middleditch, J. E. Nelson, 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.)*

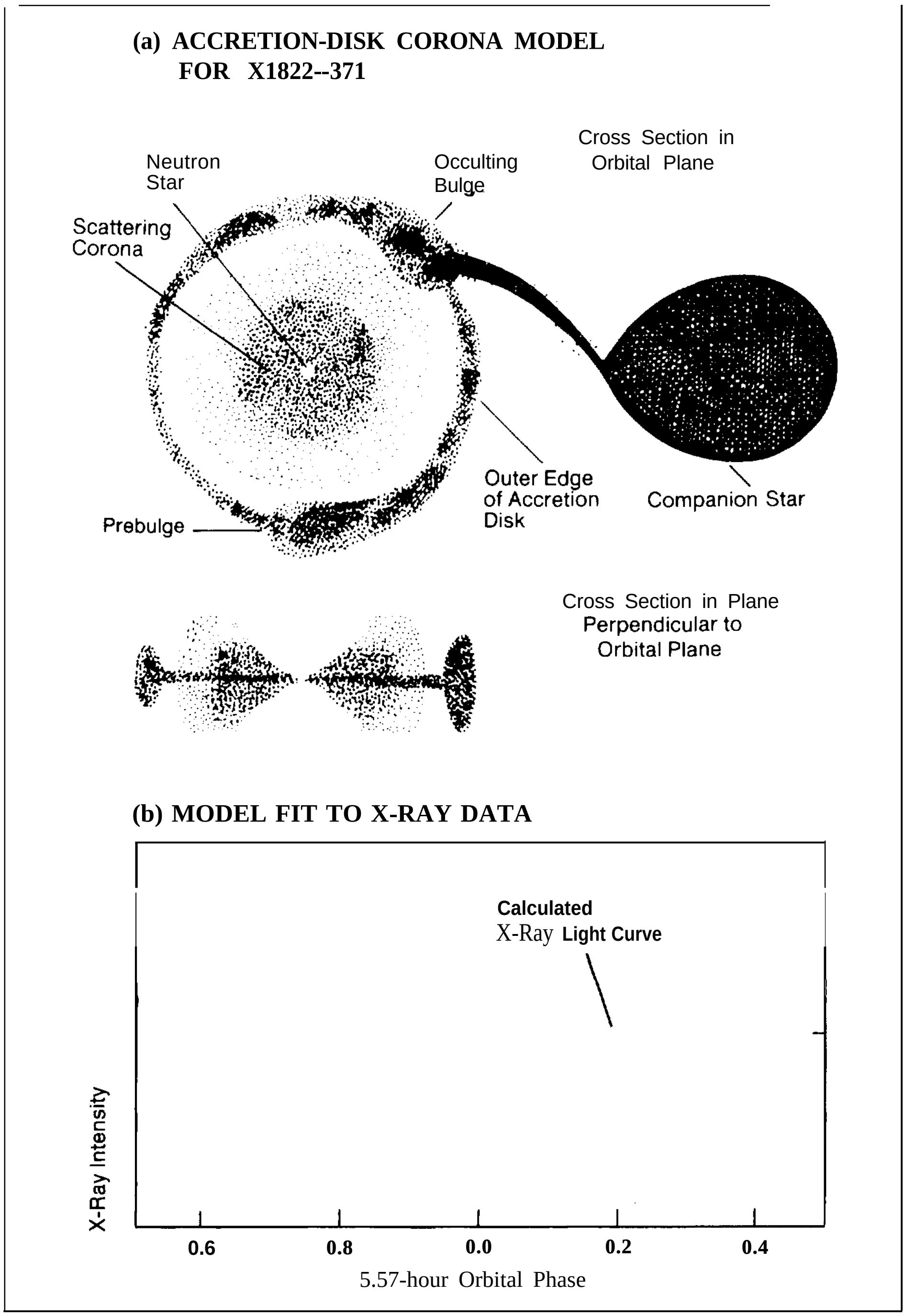


Fig. 2. An accretion-disk corona model for X1822–371 containing the structural features shown in (a), namely, a scattering corona within the disk and occulting bulges on the outer rim of the disk, can befitted, as shown in (b), to the x-ray light curve with appropriate choices for the geometric parameters 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

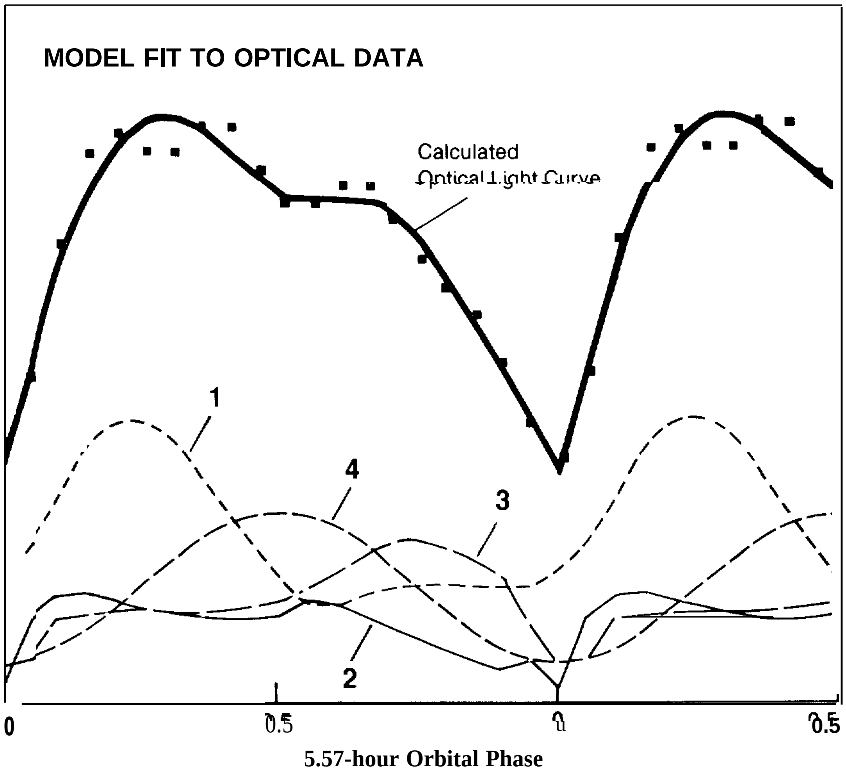


Fig. 3. If the optical radiation from X1822–371 is assumed to consist of a weighted sum of contributions from four luminous regions, its optical light curve can be reproduced well by the accretion-disk corona model. The luminous regions are (1) the inner surface of the thickened rim of the accretion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

AUTHOR

France Anne-Dominic Cordova 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.

Further Reading

Nature Physical Science (1972)239:114. The entirety of this 23 October 1972 issue is devoted to reports about the September 1972 radio-frequency outbursts of Cygnus X-3.

Baym, Gordon, Kolb, Edward W., McLerran, Larry, Walker, T. P., and Jaffe, R. L. 1985. Is Cygnux X-3 strange? *Physics Letters 160B:181*.

Becklin, E. E., Hawkins, F. J., Mason, K. O., Matthews, K., Neugebauer, G., Packman, D., Sanford, P. W., Schupler, B., Stark, A., and Wynn-Williams, C. G. 1974. Infrared, radio, and x-ray observations of Cygnus X-3. *The Astrophysical Journal 192:L119.*

Chadwick, P. M., Dipper, N. A., Dowthwaite, J. C., Gibson, A. I., Harrison, A. B., Kirkman, I. W., Lotts, A. P., Macrae, J. H., McComb, T. J. L., Orford, K. J., Turver, K. E., and Walmsley, M. 1985. A 12.6-ms pulsar in Cygnus X-3. *Nature* 318:642.

Chanmugam, G. and Brecher, K. 1985. Ultra-high energy y rays and cosmic rays from accreting degenerate stars. *Nature 313:767*.

Cordova, F. A., Mason, K. O., Priedhorsky, W. C., Margon, B., Hutchings, J. B., and Murdin, P. 1985. An imaging optical/UV monitor for X-ray astronomy observatories. *Astrophysics and Space Science* 111:265.

Geldzahler, B. J., Johnston, K. J., Spencer, J. H,, Klepczynski, W. J., Josties, F. J., Angerhofer, P. E., Florkowski, D. R., McCarthy, D. D., Matsakis, D. N., and Hjellming, R. M. 1983. The 1982 September radio outburst of Cygnus X-3: Evidence for jetlike emission expanding at >0.35 c. *The Atrophysical Journal 273:L65.*

Hillas, A. M. 1984. Is Cygnus X-3 a monoenergetic 10^{17} eV accelerator? *Nature 312:50.*

Johnston, K. J., Spencer, J. H., Simon, R. S., Waltman, E. B., Pooley, G. G., Spencer, R. E., Swinney, R. W., Angerhofer, P. E., Florkowski, D. R., Josties, F. J., McCarthy, D. D., Matsakis, D. N., Reese, D. E., and Hjellming, R. M. Radio flux density variations of Cyg X-3. Submitted in 1985 to *The Astrophysical Journal.*

Lloyd-Evans, J., Coy, R. N., Lambert, A., Lapikens, J., Patel, M., Reid, R. J. O., Watson, A. A. 1983. Observation of y rays >10^{15} eV from Cygnus X-3. *Nature 305:784.*

MacKeown, P. Kevin and Weekes, Trevor C. November 1985. Cosmic rays from Cygnus X-3. *Scientific American 253:60.*

Marshak, M. L., Bartelt, J., Courant, H., Heller, K., Joyce, T., Peterson, E. A., Ruddick, K., Shupe, M., Ayres, D. S., Dawson, J., Fields, T., May, E. N., Price, L. E., and Sivaprasad, K. 1985. Evidence for muon production by particles from Cygnus X-3. *Physical Review Letters* 54:2079.

Mason, K. O., Middleditch, J., Nelson, J. E., White, N. E., Seitzer, P., Tuohy, I. R., and Hunt, L. K. 1980. A 5.57 hr modulation in the optical counterpart of 2S 1822–371. *The Astrophysical Journal* 242:L109.

Mason, K. O., Murdin, P. G., Tuohy, I. R., Seitzer, P., and Branduardi-Raymont, G. 1982. Phase resolved optical spectroscopy of the compact X-ray binary 2A 1822–371. *Monthly Notes of the Royal Astronomical Society* 200:793.

Mason, Keith O. and Cordova, France A. 1982. Infrared photometry of the X-ray binary 2A 1822–371: A model for the ultraviolet, optical, and infrared light curve. *The Astrophysical Journal* 262:253.

Mason, K. O., Cordova, F. A., and White, N. E. Simultaneous X-ray and infrared observations of Cygnus X-3. Submitted in 1985 to *The Astrophysical Journal.*

Molnar, Lawrence A. 1985. A multiwavelength study of Cygnus X-3. Ph.D. thesis, Harvard University, Cambridge.

Molnar, Lawrence A., Reid, Mark J., and Grindlay, Jonathan E. 1984. Low-level radio flares from Cygnus X-3. *Nature* 310:662.

Waldrop, M. Mitchell. 1968. Is Cygnus X-3 a quark star? Science 231:336.

Watson, A. A. 1986. Cosmic y rays and cosmic nuclei above 1 TeV. In *Proceedings of the 19th International Cosmic Ray Conference.* Vol. 9. NASA Scientific and Technical Information Branch Office. Washington, D.C.

White, N. E. and Holt, S. S. 1982. Accretion disk coronae. *The Astrophysical Journal* 257:318.

Willingale, R., King, A. R., and Pounds, K. A. 1985. *EXOSAT* MEDA observations of Cygnus X-3. *Monthly Notes of the Royal Astronomical Society* 215:295.