Cygnus X-3: a powerful galactic source of hard radiation

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A review is given of experimental and theoretical research on the galactic source Cyg X-3, whose electromagnetic spectrum extends from radio frequencies to ultrahigh-energy ($E_\gamma \sim 10^{16}$ eV) γ rays. Cyg X-3 also has a high x-ray luminosity (10^{38} erg/sec) and exhibits diversified sporadic and periodic variations, most notably occasional radio outbursts and a $4^h.8$ infrared, x-ray, and γ-ray cycle. Analysis of the observations indicates that Cyg X-3 is a close binary system comprising a compact relativistic object (neutron star, black hole) and a dwarf companion losing mass. Particles are accelerated to 10^{16} eV within the system.

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INTRODUCTION

A great many new results have been emerging in high-energy astrophysics. X-ray bursts and pulsars, γ rays from interstellar gas impacted by cosmic rays, x-ray emitting gas in clusters of galaxies, active galaxies that generate x rays, discrete γ-ray sources in our own stellar system—these by no means exhaust all the discoveries of x- and γ-ray astronomy. In fact without these and many other findings gathered by high-altitude balloon experiments and special-purpose satellites, modern astrophysics could scarcely be imagined.

Research in high-energy astrophysics concentrates on the processes that accompany the release of huge amounts of energy. X-ray emission as a rule testifies to the thermal side of phenomena typically occurring at temperatures $T = 10^7$–10^{10} K, corresponding to mean energies $E = kT = 10^3$–10^6 eV for the emitted photons, while γ rays accompany the nonthermal (accelerative) stage of the process, during which both particles and photons reach energies of 10^7–10^{16} eV, the range characteristic of cosmic rays.

We are devoting this review to a single celestial object, the discrete galactic source Cygnus X-3, located about 10 kiloparsecs from the sun. By selecting just one object from the scores, indeed hundreds, that have now been discovered with x- and γ-ray telescopes, we are deliberately narrowing the scope of the high-energy astrophysics research being presented. The overall picture has, however, been covered by other reviews, including several in this journal.[1–4] Instead what we aim at doing here is to give a close-up view of our selected astrophysical object, focusing on its distinctive behavior toward the "hard" end of the electromagnetic spectrum. Moreover a single source can serve as an example of how objects are being studied concurrently at all wavelengths from the radio-wave region to ultrahigh-energy γ rays. But perhaps the main reason for our selection is that Cyg X-3 is a unique binary star system, in an active evolutionary phase accompanied by strongly nonstable (flare type) processes whose physics is not yet understood. Outbursts of Cyg X-3 are observed quite often, from several times to tens of times annually depending on their power, so this source is a natural laboratory where violent activity can be studied in detail.

Although Cyg X-3 has been under observation only for a little more than a decade, a good many important results have been obtained. In its wealth of notable properties Cyg X-3 to some extent surpasses even the celebrated Crab Nebula, another nonstable object in our Galaxy, formed by the explosion of a supernova. Cygnus X-3 is more powerful than the Crab, with its central pulsar, is at the present time; its radiation covers a still broader spectrum and its temporal behavior is more diversified. No wonder, then, that the observations of Cyg X-3 are furnishing abundant food for research on a side range of topics in theoretical astrophysics. The large variety of models that have lately been proposed for this source highlight the close attention that Cyg X-3 is attracting among the scientific community.

2. RESEARCH BACKGROUND IN BRIEF

Discovered[5] in 1966, at a time of momentous new findings in x-ray astronomy, Cyg X-3 was so named as it was the third x-ray source detected in the constellation Cygnus. Observations with the *Uhuru* x-ray satellite[6,7] at the start of the 1970s confirmed its status as a discrete galactic source. In the fourth *Uhuru* catalog[8] it is designated 4U 2030 + 40. Yet Cyg X-3 first aroused wide interest not in its capacity as an x-

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ray source but as a source of outbursts of radio waves.

On September 2, 1972, a group of Canadian radio astronomers recorded a powerful outburst[9,10] coming from the direction of Cyg X-3, and a second radio burst, even more powerful, followed just two weeks later.[11] News of the first event had been transmitted to all astronomical research centers and, as is the practice in such cases, every available type of instrumentation, including telescopes in orbit, was pressed into service to monitor the source.

The observers hoped above all to answer two questions: What is the optical counterpart of the source, and how does the hard radiation of the object behave during radio outbursts? At first no optical identification was forthcoming.[12,13] The source turned out to be quite distant from the sun and furthermore it is practically in the Galaxy's central plane, so a thick layer of absorbing dust conceals it from us. For this reason any optical flares which the source may have experienced in the past would not have been noticed. We can observe it only in more penetrating forms of radiation, such as radio waves and x rays, and that is why Cyg X-3 has only now become accessible to study.

Nevertheless ground-based telescopes have been able to pick it up in the near infrared, at wavelengths $\lambda = 8000$–20,000 Å, as an object of about 17th magnitude,[12,14] although its spectral type has not yet been established, due to strong reddening in the dust layer. The infrared source has proved to be highly unstable with a broad class of light variations, ranging from short flashes a few minutes long to flares lasting for days and correlated with the radio flux variations. Along with these sporadic infrared fluctuations the source has displayed modest (at about the 10% level), regular changes in flux[12] with a period $P_0 = 4^h.8$.

The initial x-ray observations, carried out during the September 1972 radio outbursts using the *Copernicus*,[12,14] *Uhuru*,[15] and *OSO* 7 orbiting stations,[16] showed that in the hard spectral region the behavior of the source is altogether different. No powerful bursts comparable to the radio events were detected; at the time of the first radio outburst the x-ray intensity changed by no more than a factor 1.5. On the other hand the x-ray emission contained a distinct periodic component contributing close to 100% of the constant level of flux.[14–17] And the x rays had the same period P_0, the same steady phase, and the same sort of light curve as the infrared radiation. It is this pulsating radiation of period P_0 which has tied together the different parts of the spectrum, decisively establishing that they represent one and the same object. Such a conclusion otherwise would have been precluded by the differing spatial resolution of the radio, infrared, and x-ray detectors. As we shall see, tests for this $4^h.8$ periodicity will continue to serve as the prime criterion for assigning a given radiation source to the object called Cyg X-3.

In the γ-ray range, excess high-energy[18] ($\sim 10^8$ eV) and very high-energy[19] ($\gtrsim 10^{12}$ eV) flux from the Cyg X-3 region was recorded as early as September–October 1972, while the source was still in its active state. But the measured γ rays were not definitely allocated to Cyg X-3 until several years later, after enough material had been acquired so as reliably to establish that the γ rays are pulsating[20,21] with the same period P_0.

The behavior of the pulsating γ-ray emission was found to differ fundamentally from the x-ray and infrared light curves: instead of a smooth sine wave, narrow individual pulses were observed. These each lasted $\approx 0.2P_0$ for the high-energy γ-ray photons, and were as short as $\approx 0.05P_0$ for the very hard radiation: at energies $E \geqslant 10^{12}$ eV the pulses were just 15 min wide! Their amplitude proved to vary as well, being greater during periods of enhanced radio activity, although as in the x-ray range there was no direct correlation with the radio outbursts.

A resurgence of interest in Cyg X-3 occurred early in the 1980s with the discovery of a second, lengthier period[22,23] $P_1 \approx 34^d$, indicating that the source is a richer, more complex object than hitherto believed. A refinement of the x-ray light curve[24] and the confirmation of the narrow pulses of very hard γ rays reported by several other groups[25–27] who had previously given only upper limits on the intensity have heightened the fascination even further. The latest in this chain of discoveries concerning Cyg X-3 (and, one would hope, not the last) has been the detection by extensive air-shower apparatus[28,29] of its emission of ultrahigh-energy ($E = 10^{15}$–10^{16} eV) γ rays.

All these findings underscore once again how strange, unique, and complicated a source Cyg X-3 is. They have prompted the development of any number of theoretical models for the source. It is now evident that Cyg X-3 is one of the most powerful sources in the Galaxy. The source releases most of its energy in the hard spectral regions. Its x- and γ-ray luminosity reaches 10^{37}–10^{38} erg/sec and remains at a high level up to ultrahigh energies. As a matter of fact this is the first case in astrophysics where an object is generating particles as energetic as 10^{16} eV before our very eyes.

3. OBSERVATIONAL RESULTS

We turn now to a detailed survey of the observational evidence on Cyg X-3 that has been gathered in the different parts of the electromagnetic spectrum over the past decade. To provide a better grasp of these experimental results we will often need forthwith to offer a qualitative interpretation. A fuller analysis of the observational data will be given when we discuss some models of the source in Sec. 4.

a) Radio emission

The object whose outburst was observed at radio wavelengths on 1972 September 2 had earlier been recorded as a weak, variable radio source.[30] Its fluctuating intensity had been measured during 1972, and just two days before the outburst[31] was at a level[1)] of 0.01 – 0.04 Jy in the 2–8 GHz frequency interval. During the outbursts the flux leaped by a factor of more than 10^3 and then declined smoothly over the next few days. Peak flux densities of[10,32] $F_1 = 22$ Jy and[33] $F_2 = 14$ Jy were registered at these frequencies in the September 2–11 and September 19–26 outbursts, respectively.

Figure 1 shows the outburst time profiles measured at two lower frequencies, 365 and 408 MHz. The second outburst here seems considerably more powerful than the first, but actually it was a compound event comprising three separate bursts at intervals of several days, a structure particular-

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[1)] The jansky is a unit of spectral flux density; 1 Jy $\equiv 10^{-26}$ W m^{-2} Hz^{-1}.

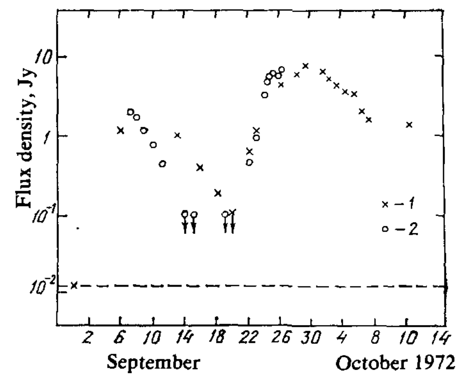

FIG. 1. Variations in the radio flux density of Cyg X-3 during September 1972 (Gregory *et al.*[10]). *Dashed line*, radio-emission level while the source was in its quiescent state. 1) $\nu = 365$ MHz; 2) $\nu = 408$ MHz.

ly noticeable at high frequencies.[34]

Beginning with the earliest efforts[3,4] to interpret the radio outbursts of Cyg X-3, the burst emission was attributed to synchrotron radiation of a cloud of relativistic electrons ejected from the object and moving in its magnetic field. Support for the synchrotron nature of the radio emission has been obtained from measurements of the burst frequency spectrum and linear polarization.

1. Frequency spectrum. Figure 2 displays time profiles of the radio emission measured at four different frequencies during the first September outburst.[34] At each frequency the flux initially rose to a peak value and then began to diminish smoothly. Maximum partial flux at first was reached at high frequencies, but when the 8.1–10.5 GHz flux had begun to weaken, the 1.4 – 5.0 GHz intensity was still growing.

One can interpret these profiles by supposing that as the electron cloud expands, its optical depth $\tau = R/l$ varies (R is the cloud radius, l is the photon mean free path). In the radio range l increases with frequency, so τ will always be smallest for high-frequency radiation. So long as the cloud is compact and dense, it will be opaque to radio emission of all frequencies—the case of an optically thick cloud ($\tau \gg 1$). The radio flux emitted by an optically thick source will grow with time as R^2, in proportion to the increasing area of the radiating surface. When the cloud has expanded and its density has dropped to the point where l becomes comparable with its size R, the cloud will be optically thin ($\tau \lesssim 1$). Radiation will escape freely, and the flux will reach its peak value. As the optically thin cloud continues to expand, the electrons' energy will be weakened by adiabatic, synchrotron, and other losses, and the radiation flux will steadily wane.

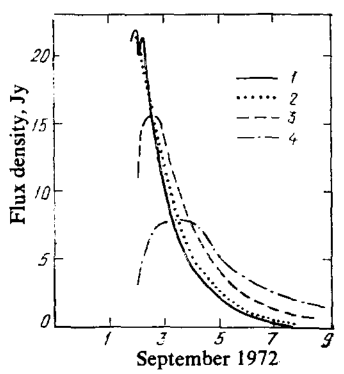

FIG. 2. Time profiles of the radio emission in the original outburst at several frequencies (Gregory *et al.*[34]). 1) 10.522 GHz; 2) 8.085 GHz; 3) 2.695 GHz; 4) 1.42 GHz.

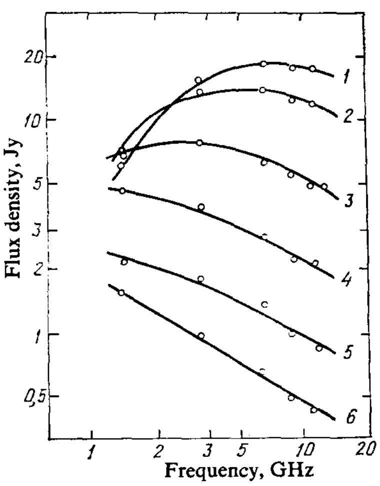

FIG. 3. Evolution of the Cyg X-3 radio spectrum during the original outburst (Gregory *et al.*[34]). 1) 1972 Sep $3^d 12^h$ UT; 2) Sep $4^d 0^h$; 3) Sep $5^d 0^h$; 4) Sep $6^d 0^h$; 5) Sep $7^d 0^h$; 6) Sep $8^d 0^h$.

The frequency spectrum of the radio emission undergoes substantial modifications during an outburst, evolving as illustrated in Fig. 3. In this case immediately after the outburst commenced, while the cloud was optically thick at many of the frequencies recorded, the spectrum was heavily distorted by self-absorption of radio waves in the source (curves *1, 2*). Soon the cloud became transparent at high frequencies; the corresponding radiation escaped without being distorted, but there was still a noticeable falloff toward lower frequencies (curves *3, 4*). Eventually the condition $\tau < 1$ was satisfied throughout the frequency range, and the radiation emerged from the cloud with its spectrum undistorted (curves *5, 6*). The spectrum could now be represented by a single power law, $I(\nu) = A\nu^{-\alpha}$, the very spectrum that the synchrotron radiation of electrons should have in a uniform or slightly space-variable magnetic field[35] if the electrons conform to a power-law energy spectrum $I(E) = BE^{-\beta}$. The exponents α, β are related by $\beta = 2\alpha + 1$. Measurements during several Cyg X-3 outbursts[32] yield radio spectral indices $\alpha = 0.2 - 0.6$, implying electron energy spectra with exponents $\beta = 1.4 - 2.2$.

Incidentally the expanding cloud contains not only relativistic electrons but thermal plasma, which will contribute to the absorption of radio waves.

2. Polarization. When the outburst radio emission was found to be linearly polarized, its synchrotron origin was confirmed. In the first 1972 outburst, however, the linear polarization at $\nu = 10.5$ GHz amounted[32] to only $\eta = 4\%$ rather than the tens of percent predicted by theory.[35] This circumstance indicates that the radiation is being severely depolarized by Faraday rotation of the polarization plane within the optically thick envelope. The plasma electron density calculated on this basis was found to be $n_e = 10^7$ cm^{-3}.

In a subsequent series of outbursts the percentage linear polarization proved to be higher, confirming not only the synchrotron nature of the radiation but also the depolarization in the cloud. For example, in the 1974 May 14 outburst a polarization $\nu = 14\%$ was recorded[32] at $\nu = 2.7$ GHz, suggesting an optically thin envelope with an electron density of only $\approx 10^2$ cm^{-3}.

Measurements have also been made of the circular radio polarization η_c, whose presence would indicate that the electrons may have an anisotropic pitch-angle distribution[36] and also could serve to diagnose the charge composition—the electron/positron population ratio in the cloud.[37] But no perceptible circular polarization has been detected. The upper limit obtained,[32] $\eta_c = 0.5\%$, implies that the source is symmetric, with equal contributions coming from regions of opposite magnetic polarity corresponding to oposite senses of circular polarization.

3. Source location. The distance of Cyg X-3 has been established from the absorption of its radio waves in interstellar atomic hydrogen. Comprising the bulk of the interstellar gas, atomic H resonantly absorbs radiation of 21-cm wavelength. Differential galactic rotation will Dopler-shift the absorption lines from different parts of the Galaxy, blending them into an absorption band whose width provides an estimate of the object's distance. Such measurements demand high accuracy along the spectrum, and the first attempts to apply the method to Cyg X-3 yielded only an upper limit[10,11,38] indicating that the source lies inside our Galaxy. More careful measurements later established a finite distance[33]: $r = 10.0 \pm 1.5$ kpc. Some doubt has been expressed in the accuracy of these measurements, however, and certain evidence suggests the source may be more distant.[39,40]

In any event, Cyg X-3 is so remote from the terrestrial observer that its recorded level of flux density implies a high intrinsic luminosity. Even in its quiescent state the luminosity of the radio source would be of order 10^{31} erg/sec; during outbursts it would reach 10^{35} erg/sec, a value comparable with the luminosity of young supernova envelopes such as Cassiopeia A.

The angular size of the Cyg X-3 radio source has been determined by very long baseline interferometry (the VLBI technique) at 3.6-cm wavelength[41]: in its quiescent state the angular diameter is $(13 \pm 2) \times 10^{-4}$ arc sec. If we accept that the distance of the source is $r = 10$ kpc, the emission region would measure about 2×10^{14} cm across. Thus far the longest VLBI baseline used has been 3600 km; even longer baselines will be needed to clarify the structure of the object.

Measured just as precisely,[32] the celestial coordinates of Cyg X-3 are: right ascension $\alpha = 20^{\mathrm{h}}30^{\mathrm{m}}36^{\mathrm{s}}.620$, declination $\delta = 40°47'12''.85$ (1950.0). This accurate position for the radio source permits a deep search for the object in the optical and infrared ranges (Sec. 3b).

4. Long-term observations. Cygnus X-3 has been kept under observation with radio telescopes for the past dozen years,[10,32,42–54] and numerous outbursts have been recorded. Table I reproduces Woodsworth's list[55] of the Cyg X-3 radio flares during the 1972–1982 period. Outbursts with a peak flux density $F_{\max} > 1$ Jy occur twice a year, on the average. Often the events are grouped, following each other at short intervals: double and triple bursts were observed in September 1972, June–July 1973, December 1973, May 1974, and January 1975. The occurrence of weak and strong flares does not show any periodicity. Clearly the source was an active burster during 1972–1975; in the late 1970s the activity dropped off markedly. Perhaps that is why such strong bursts as those of September 1972 did not recur for quite some time.

TABLE I. Radio outbursts of the Cyg X-3 source[55] with peak flux density above 1 Jy.

Date, UT	Frequency, GHz	Maximum flux density, Jy	Reference No.
1972 Sep 2.5	10,6	22	10
Sep 20.6	5	12	42
Sep 23.5	2,7	15	42
Sep 27.3	1,4	12	33
1973 Jun 8.0	5	3	48
Jun 14.0	5	7	48
Jul 1.3	10,6	7	44
Oct 8.2	10,6	4	49
Dec 24.1	4,2	8	45
Dec 31	4,2	6	45
1974 May 13.4	5	7	48
May 20.0	8.1	12	32
Dec 19.1	4,2	5	46
1975 Jan 10	5	10	51
Jan 29.5	8	7	50
Aug 25	5	15	51
1977 Dec 18.7	22	4	52
1980 Sep 26.9	22	10	53
1982 Oct 5.5	10.7	4	54

In September–October 1982, however, a series of outbursts took place which were as strong as the most powerful hitherto recorded.[56] At. 8.1 GHz the peak flux density was 22 Jy. Interferometer (including VLBI) observations have shown that electrons were ejected in two opposite directions (roughly along a north–south line) at angular speeds of $(0''.010 \pm 0''.002)$/day. If the source is 11.6 kpc away from us (the lower limit suggested by recent observations[40]), the electron clouds would be shooting out at a velocity $u = 0.35c$, where c is the speed of light. Thus during an outburst the electron beams are traveling at relativistic velocities, and the whole picture of the Cyg X-3 flare radio emission is very like what we observe in extragalactic radio sources, radio galaxies, and quasars.

Old records have been reinspected[33] and the source has been found to have experienced flare activity even earlier, such as in 1964–1965, but more weakly than in 1972–1973.

From the long-term observations it appears that each outburst has a temporal fine structure comprising an irregular sequence of rises and dips in the radio flux. This fine structure replicates the idiosyncrasies of the electron surges—their temporal, spatial, and spectral characteristics—and it warrants thorough study and comparison against models of the burster. Several early models of the Cyg X-3 radio outbursts[34,57,58] relied on the synchrotron radiation of a relativistic-electron cloud in the magnetic field of a nonstable star. Analysis of the observational data for the first September outburst in terms of one such model[57] indicated that in a single day a cloud of mass $0.7 \times 10^{-8} M_{\odot}$ had been thrown off ($M_{\odot}$ denotes the mass of the sun).

b) Infrared radiation

The absorption and scattering of light in the gas and dust layer interposed between the source and the earthbound observer hinder an optical identification of Cyg X-3. In the near-infrared spectral region, however, the gas–dust medium is more transparent, and large telescopes on the ground have been employed to search for an infrared object at the position of the radio source in the sky. Observations in the I wavelength band of the infrared spectrum (mean wavelength 0.85 μ) initially revealed no starlike object[13,39,59] brighter than $17^m.5$. At longer wavelengths, in the H and K bands ($\bar{\lambda} = 1.6$ and $2.2\,\mu$), the source was in fact detected[12,14] in an observing program undertaken with the 200-inch telescope in 1972–1973.

Cygnus X-3 is strongly variable in the infrared range: sporadic flares lasting from minutes to hours are observed, as is a periodic modulation[12,14] of the radiation. The periodic component, which contributes $\approx 10\%$ of the total infrared flux, has a near-sinusoidal light curve with a period $P_0 = 4^h.8$. The value of P_0 is maintained to just as high a precision as the periods of pulsars, and yet is incomparably larger. It is quite natural to conjecture that P_0 represents the orbital period of a binary star. We would then be dealing with a very close binary system, the two stars being separated on the average by $a \approx 10^{11}$ cm $\approx 1.5\, R_{\odot}$.

Fairly recently Cyg X-3 was also detected in the near infrared, in the 0.8–1.0 μ wavelength interval. Two telescopes at the Mount Hopkins Observatory in Arizona were used.[60] An image was formed at the telescope foci by charge-coupled devices (CCDs), matrices of 512×320 cells each measuring $30\,\mu \times 30\,\mu$. To diminish the dark current the CCD was chilled to $-155\,^{\circ}$C and operated on-line with a computer. Four of the exposures showed a stellar object within 1″ of the radio-source position. Cygnus X-3 is projected against a galactic spiral arm, so its field contains quite a few other stars. The object is of apparent magnitude $17^m.0 \pm 0^m.2$, and seems to be variable on a time scale of two months. The $4^h.8$ periodicity is distrinctly superposed, reaching 30% amplitude.

The CCD detector was calibrated against stars in the galactic background and in the nearly globular cluster M67. From measurements of the object's apparent magnitudes in the K, R, I infrared wavelength bands, differences (color indices) $\Delta m_{KI} = 5^m.6$, $\Delta m_{RI} = 3^m.6$ were formed, and the reddening technique[61] was applied to estimate the number of H atoms in a column along the line of sight. This method yields the total column density of hydrogen, in both atomic form (H I regions) and molecular form (cool, dense gas clouds), along the way from the source to the observer. The measured value, $N_{\text{IR}} = 3 \times 10^{22}$ atoms/cm^2, agrees closely with the column density N_x derived from the absorption of soft x rays in the source,[6,7] and is approximately twice the value N_r deduced from the self-absorption of radio waves.[33] Qualitatively one can interpret these results as follows: while the infrared radiation and x rays are emanating from the same spatial zone in the source, the radio emission is being generated somewhere else, in an outlying region of the object.

This program of infrared observations was carried out when the source was in its quiescent state. If it could be observed at the time of an outburst concurrently with measurements of its x-ray emission, the results might help to put serious constraints on the viable models of the source.

c) X-ray emission

Although the radio and infrared observations first pointed up some important peculiarities of Cyg X-3, the object has been investigated most thoroughly in the x-ray range. Plentiful information has been secured on the x-ray emission, thanks not only to physical factors (the intensive hard-radiation activity of the source, the great penetrating power of the x rays) but also to the purely observational capabilities of modern astronomy. No branch of observational astronomy has lately undergone such swift development as x-ray astronomy. Cygnus X-3 has been one of the objects most often placed on observing programs: satellite-borne x-ray telescopes have given it weeks and months of exposure, ultimately bringing in an immense amount of information.

Observations have been made with various types of x-ray detectors, encompassing the whole x-ray range from photons of about 1 keV to 400 keV energy, and throughout this region the measurements show finite intensities. The only exception is the soft x-ray interval, 0.1–1 keV; here a finite flux has not been detected, due to severe absorption by interstellar gas (the mean free path of a 200-eV photon[62] is ≈ 50 pc).

In the "classical" x-ray region, 2–12 keV, the fullest results have been acquired with the x-ray telescope aboard the Eurepean *COS-B* satellite,[24,63] which functioned continuously for 6.5 years in orbit (1975–1981). During this interval *COS-B* devoted four exposure-months to the part of the sky where Cyg X-3 is located: November 1975, June 1977, November 1978, and May–June 1980. The individual observing sessions differed in efficacy, for each time the telescope axis was pointed not directly at the source but a few degrees away, mainly so that the field of view would not also be accepting radiation from the still brighter x-ray source Cyg X-1.

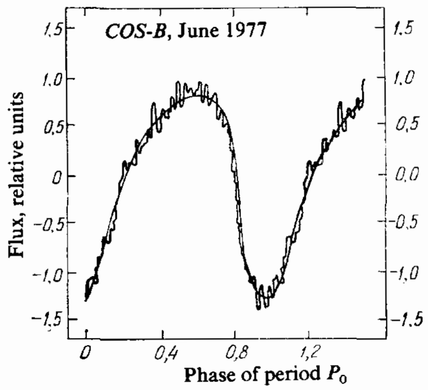

FIG. 4. Mean x-ray light curve of Cyg X-3, based on the period $P_0 = 4^h.8$ (Bonnet-Bidaud and van der Klis[24]).

TABLE II. Periodic-radiation parameters of Cyg X-3.

Spectral range	Period P_0, day	Initial epoch, JD	Period derivative $\dot{P}_0$	Period P_1, days
Infrared radiation	0,199679 (7)[14]	2441872,820[14]		
X rays, $E = 2$–12 keV	0,1996830 (4)[66]	2440949,8986[66]	$(1{,}18 \pm 0{,}14) \cdot 10^{-9}$ [66]	34.1±0,1 [22]
γ rays, $E \sim 10^8$ eV	0.199686 (5)[67]	2440949.917[64]		
γ rays, $E \sim 10^{12}$ eV	0,199683 (1)[68]	2441550,542[68]	$(3{,}0 \pm 1{,}4) \cdot 10^{-9}$ [68]	34.02 [69]
γ rays, $E \sim 10^{15}$ eV	0,1996816(2)[28]	2440949.9176[29]		34? [28]

1. Periodic component. Radiation pulsating with the period $P_0 = 4^{\mathrm{h}}.8$ is far more striking in the x-ray than in the infrared range: relative to the steady level the periodic x-ray component reaches nearly 100% amplitude. Figure 4 shows the light curve averaged over numerous separate pulses.[24] What was initially thought to be a sine wave actually is a significantly different curve, asymmetric about its maximum, with the rise less steep than the decline. The geometry of the binary system is evidently responsible for the light curve having this shape, which should be taken into account when constructing models for the source.

In all the energy ranges measured, the period P_0 and initial epoch φ_0 are the same. The most accurate values of P_0, φ_0 are given in Table II. Determined to eight decimal places, P_0 is increasing with time: its first derivative, based on various measuments,[16,17,64] is $\dot{P}_0 = (1.2$–$3.7) \times 10^{-9}$. This value agrees with a result lately obtained with the *Einstein* orbiting observatory[65]: $\dot{P}_0 = (1.8 \pm 0.4) \times 10^{-9}$. Accordingly the relative lengthening of the period amounts to $\dot{P}_0/P_0 = 3.3 \times 10^{-6}\ \mathrm{yr}^{-1}$.

Long-term observations of the x-ray source have shown that the amplitude I_1 of the periodic component and the intensity I_0 of the nonpulsating, steady flux also vary with time. Concurrent measurements of I_0, I_1 during two settings of the *COS-B* telescope on the source[24] are plotted in Fig. 5. The flux variations are not monotonic, and I_0, I_1 are definitely correlated with each other. In general the correlation is nonlinear, so that the periodic component may grow sharply in amplitude while the steady flux rises only modestly.

The shape of the x-ray light curve itself confirms the time variations, for it remains as depicted in Fig. 4 if averages are taken over comparatively long intervals (at least a month). On shorter time scales, however, the light curve may change shape from one measurement to another, as indicated by Fig. 6, which plots separately the average results from four week-long exposures.[24] These changes in the light-curve shape affect its asymmetry and shift the position of the maximum. On occasion the asymmetry will disappear completely, the curve becoming practically symmetric. It is noteworthy that the modifications in shape correlate with the level of I_0: the symmetry improves as I_0 increases. Once I_0 has reached a certain level (≈ 30 counts/sec for the *COS-B* detector[24]) the symmetry is optimized. All these light-curve fluctuations refer to times near maximum of the long-period cycle (see next subsection); at minimum phase the x-ray light

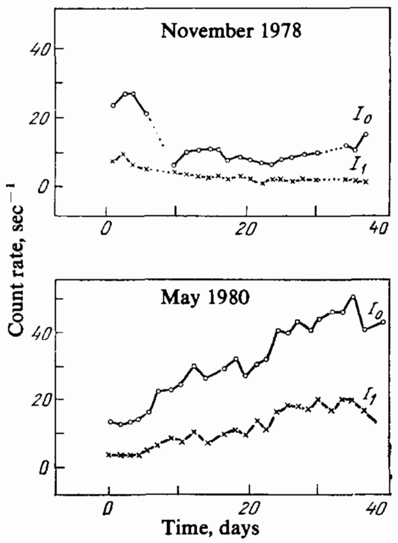

FIG. 5. Typical long-term variations of the steady and periodic components I_0, I_1 of the x rays[24] from Cyg X-3.

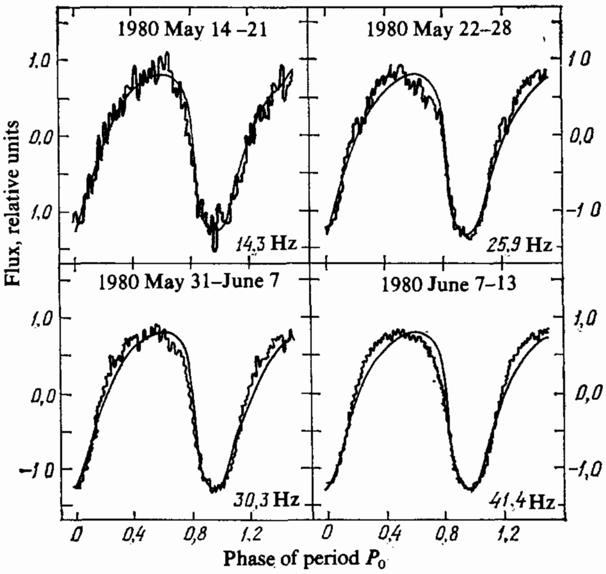

FIG. 6. Light curves for the periodic x-ray component recorded in four successive 1-week exposures[24] of Cyg X-3. The mean count rate is indicated in each case.

curve maintains a constant profile, independent of the I_0 level.

One can qualitatively interpret the observed x-ray behavior of Cyg X-3 in the following way. Presumably the asymmetry of the light curve reflects the eccentricity of the binary-system orbit. The smoothness of the light curve, very different from the eclipse curves of x-ray pulsars,[4,70] testifies to an abundance of gas scattering the x-ray photons either within the binary system or in the immediate neighborhood of the source.

X rays from the source will pass through the absorbing and scattering medium, so that the flux we record will consist of two components, the transmitted and the scattered flux. We may write this intensity as

$$I = I_{\text{init}}\,[f(\varphi)\,e^{-\tau} + g(\varphi)\,(1 - e^{-\tau})], \qquad (1)$$

where I_{init} denotes the initial x-ray flux from the interior source; $f(\varphi)$, $g(\varphi)$ are certain functions of the phase of the period P_0, reflecting the eccentric orbital motion of the x-ray source; and τ is the optical depth of the gas. Such reprocessing of the x rays from the interior source by the gas surrounding it might explain the observed shape of the light curve and its variations. A quantitative fit can be obtained by supposing that τ ranges from 0.5 to 2, depending on the value of I_{init}. Pringle[58] offered an explanation of this kind in a model whereby stellar wind shed by the companion star would induce the activity in the x-ray source.

2. Long-period variations. X-ray measurements have disclosed great diversity in the temporal behavior of Cyg X-3. Apart from pulsations with period P_0 that gradually increase with time, transient sporadic fluctuations, and long-term trends in the level of I_0, variations with a period $P_1 = 34^d$ have been detected.[22,23] There has also been other evidence for long-period variations,[24,71] but a definitive result has energed from analysis of the *COS-B* x-ray data.[22] The commencement time $t_{\min}$ of the minimum in this periodic component $I_1(t)$ deviates from the predicted time by an amount Δt which fluctuates with amplitude $t_0 \approx 200$ sec and period $P_1 = 34^d.1 \pm 0^d.1$. These Δt variations could represent periodic changes in the distance between the x-ray source and the observer. In that event the quantity $ct_0 \approx 6 \times 10^{12}$ cm would measure the extent of the system along the line of sight, and may be used to determine the observer's orientation relative to the Cyg X-3 binary system.

The period P_1 ought to manifest itself directly in the x-ray intensity. However in the 2-12 keV energy range, where P_1 was originally identified, the intensity depends only very weakly[22] on the phase ψ of the period P_1. If strong background scattering by the ambient gas is responsible, then as the photon energies increase and the contribution from the background flux diminishes, the x-ray intensity should depend more clearly on the phase ψ, and that is what is observed. Data acquired by the *OSO 8* satellite,[23] which recorded photons of 20 – 110 keV energy, show that the flux definitely depends on ψ. Two ψ-intervals can be distinguished: during the first interval ($\psi = 0.3 - 0.8$) the periodic (P_0) component is prominent and contributes $\approx 50\%$ of the flux ("favorable" phases ψ), while in the second interval ("unfavorable" phases $\psi = 0.8 – 1.0, 0.0 – 0.3$) no periodic radiation has been detected at all (any such contribution amounts to less than 25%). Other hard x-ray observations of the source,[72,73] although based on more limited material, are compatible with this finding. The discrimination of the period P_1 and its subdivision into favorable and unfavorable phase intervals becomes even more decisive and trustworthy in the very high-energy γ-ray region (see Sec. 3e).

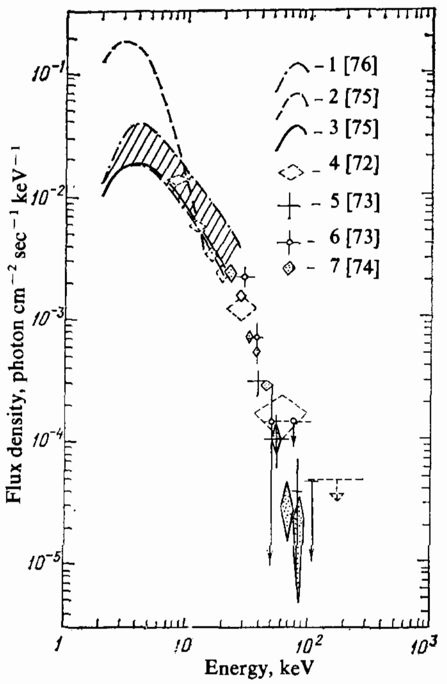

FIG. 7. The differential energy spectrum of the x-ray emission from Cyg X-3 according to various experiments (reference numbers bracketed).

3. Energy spectrum. Cygnus X-3 has been measured spectrophotometrically in all parts of the x-ray spectrum. Figure 7 illustrates the differential spectrum of the source. On the low-energy side it seems to turn over and to fall off, probably because of absorption within the source, although these results are not yet very definite. The rest of the spectrum can be represented by the exponential law $e^{E - E_0)/kT} \times (kT = 20\text{ keV})$ corresponding to thermal plasma emission declining rapidly with photon energy and therefore describing the comparatively soft portion of the spectrum, together with the power law $(E/E_0)^{-\alpha}$ characterizing the hard end of the spectrum.[74,75] The spectral index α for this portion fluctuates significantly from measurement to measurement; conceivably these fluctuations in α may result from its dependence on the phase φ of the periodic x-ray component. Some measurements[74] yield an index $\alpha = 3.6 \pm 0.3$ for the phase interval $\varphi = 0.18 - 0.60$, while others[77] indicate a substantially harder spectrum, with $\alpha = 2.2$, for the interval $\varphi = 0.45 - 0.90$. If one extrapolates the latter spectrum toward still higher energies one obtains a good fit to the γ-ray data.

According to the *Uhuru* measurements[8] the mean x-ray intensity of Cyg X-3 was 385 counts/sec, which, converted to flux-density units, is equivalent to $F_x(2\text{–}10\text{ keV}) = 9.2 \times 10^{-9}$ erg cm^{-2} sec^{-1}. Taking the source to be at 11.6-kpc distance[40] we obtain an x-ray luminosity L_x(2–10 keV) $= 1.4\times10^{38}$ erg/sec.

One drawback of the x-ray spectrum measurements is that they have been carried out with assorted instruments, at different times, and without attempting to separate out the periodic and quasisteady flux. These data merely furnish information on the average spectrum of the source, even though, as we have seen, the time fluctuations might be very substantial. Indeed the x-ray intensity of the source seems to be fluctuating continually,[14,17,78] and yet no major changes in the x-ray flux or its spectrum have been encountered during radio outbursts.

Studies of individual lines in the x-ray spectrum of Cyg X-3 are just beginning. Thus far only one line has been observed with any confidence, the iron line at $E = 6.7$ keV; its intensity[75] was found to be 1.8 ± 0.4 photons $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$.

d) High-energy (10^7–10^{10} eV) γ rays

It is the study of Cyg X-3 in the γ-ray range which, in our opinion, offers the greatest interest. The characteristic 0.1–10 MeV line emission and the higher-energy γ rays generated through the interaction of accelerated particles with surrounding matter may convey valuable information on the makeup of the source, its physical state, and the acceleration and emission processes. At present, experiments to measure the softer γ rays are only in their beginning stage, and hardly any spectroscopic measurements of γ-ray lines have yet been made. A definite result has not even been obtained for such a relatively "bright" line as the electron–positron annihilation line.

The high-energy interval of γ-ray photons has been much more fully explored. Even the initial experiments conducted with high-altitude balloons had recorded an excess (compared with the atmospheric background) γ-ray flux coming from the constellation Cygnus,[79–82] but the telescopes' angular resolution was too low to establish a unique source. The excess flux of γ-ray photons was first assigned to the source Cyg X-3 by our Moscow group[18] in 1973.

The spark-chamber γ-ray telescope had an angular resolution $\Delta\theta = 3.5°$, averaged over the spectrum of the radiation it accepted.[83] Our identification of the γ-ray source within a circle of radius $\Delta\theta$ relied entirely on the peculiar behavior of Cyg X-3, which at that time was in an active state, according to the radio observations. Moreover the first γ-ray measurements, obtained on 1972 October 12, were consistent with the idea that the telescope, pointing in the zenith direction, was viewing a single discrete source. The γ-ray flux exceeded the atmospheric background by 3.6σ, where σ is the standard deviation.

This same balloon-borne γ-ray telescope observed the source on two other occasions, (July 10, 1974 and July 5, 1976), each time[67] for about 5^{h}. Taken together, the three observing sessions further supported the original identification of the excess γ-ray flux with the object Cyg X-3. Figure 8 summarizes the results obtained.

On all three occasions γ-ray pulses lasting $\approx 1^{\mathrm{h}}$ were recorded at the same phase of the period P_0 ($\varphi = 0.0 - 0.2$). At other phases no radiation in excess of the natural atmospheric background fluctuations was detected. Accordingly one may conclude that the γ rays are being emitted periodically, with the same period P_0 as observed in the x-ray range. The value of the period can be refined by noting the position of the three γ-ray pulses during the overall 3.7-yr interval of observation: $P_0(E_\gamma \sim 10^8\ \mathrm{eV}) = 0^{\mathrm{d}}.199686(5)$, in good accord (Table II) both with the x-ray period and with the period derived from the very high-energy γ rays. The pulsating character of the γ-ray emission certainly identifies it with the source Cyg X-3, despite the comparatively low accuracy of these observations.

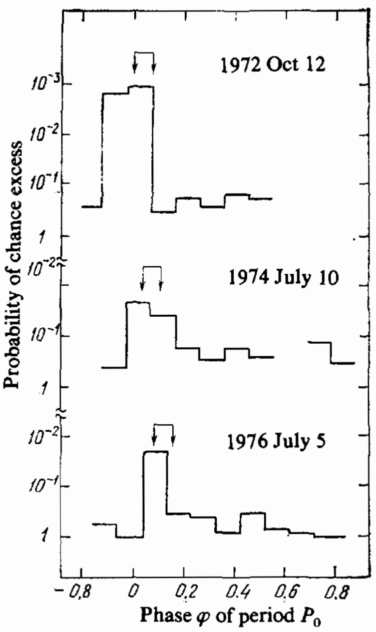

FIG. 8. Successive observations of Cyg X-3 at energies $E_\gamma > 4\times10^7$ eV with a balloon-borne γ-ray telescope (Gal'per *et al.*[67]). Arrows mark the phase of the peaks observed in the very high-energy range.

Averaged over the three measurement sessions and the period P_0, the intensity $I(E_\gamma > 4\times10^7\ \mathrm{eV}) = (6.4 \pm 2.7)\times10^{-5}$ photon $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$. During the first session, when the source was in an especially active state, the measured flux was approximately twice the average.

Gamma rays from Cyg X-3 in this same energy interval were also measured by the *SAS 2* satellite.[84] The pulsating behavior with period P_0 was confirmed, but some differences were found as well: the flux was lower (by a factor of ≈ 3 for comparable energies), and the γ-ray pulse occurred instead at phase $\varphi = 0.5 - 0.8$ of the period P_0.

Other series of balloon observations[85–87] failed to detect γ rays from Cyg X-3; but these measurements were of short duration, so that the radiation pulses might have occurred outside the exposure intervals. The upper limits obtained are not much different from the intensities that have been successfully measured.[67,84] More significant, perhaps, is the lack of any positive effect when Cyg X-3 was observed with the *COS-B* satellite.[88] Five exposures of the source region during 1975–1980 disclosed no γ-ray emission with period P_0. At the 2σ level an upper limit $I(E_\gamma \geqslant 50\ \mathrm{MeV}) < 3\times10^{-6}$ photon $\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$ was placed on the intensity.[88] This result would decidedly conflict with the earlier measurements[67,84] if the γ-ray pulse remains constant with time. But if, like the x rays, the γ-ray emission is variable, one could reconcile all the measurements by supposing that in 1975–1980 the periodic γ-ray component was several times weaker than during 1972–1975. It is interesting indeed that just the same qualitative behavior, a weakening of the source in the late 1970s, is also manifest in the radio data (Table I) and perhaps in the measurements of γ rays at very high energies[69] (Sec. 3e).

One also has to consider the modulation of the γ-ray flux that might result from the "favorable" and "unfavorable" phases ψ of the long peiod P_1 of the x-ray source. Analysis indicates that while all three of the balloon observations[67] of Cyg X-3 occurred during favorable ψ-intervals, some of the *SAS 2* and COS-B measurements[84,88] were made at unfavorable phases. This circumstance considerably mitigates the disparity in the γ-ray intensities measured by the different groups.

Two of the authors have recently analyzed the periodic γ-ray emission[89] and have been able to reconcile even more closely various observations which at first had seemed incompatible. We also find[89] that the high- and very high-energy γ-ray pulses occur in one of two places in the P_0 phase curve: at phase $\varphi \approx 0.2$ if the P_1 phase lies in the interval $\psi \approx 0.0 - 0.5$, and at $\varphi \approx 0.6$ if $\psi \approx 0.5–1.0$. Thus the radiation pulse wanders along the phase-φ curve, an effect not previously encountered in high-energy radiation sources. Undoubtedly this fact is of vital importance not only for reconciling the discordant results but also for understanding the nature of Cyg X-3.

The γ-ray luminosity of Cyg X-3 is exceedingly high, far above that of all other known γ-ray sources in the Galaxy. If its radiation is isotropic, the source would have a luminosity $L_\gamma(\geqslant 40\ \text{MeV}) = 3\times 10^{38}$ erg/sec, or around 10% the power of the whole Galaxy at these energies! If instead the emission is confined to a solid angle of, say, 1 sr, as certain pulsar models assume,[90,91] then Cyg X-3 would be an order of magnitude less luminous, but it would still be 10^2 and 10^3 times as powerful a γ-ray emitter as the young Crab Nebula and Vela X pulsars PSR 0531 + 21 and 0833 − 45, respectively. Galactic γ-ray sources as bright as this certainly must be rare; otherwise it is they which would generate the great majority of the Galaxy's γ rays, rather than the interaction between cosmic rays and the interstellar gas, presently believed responsible for the diffuse component. At these energies discrete sources are estimated[92–94] to contribute collectively less than half the total galactic γ-ray flux.

e) Very high-energy (10^{12} – 10^{14} eV) γ rays

When its γ-ray photons reach energies of order 1 TeV, Cyg X-3 becomes so weak a source that it can only be observed by recording the secondary effects of the electromagnetic cascades that it triggers in the earth's atmosphere. In fact a satellite-borne detector of 1-m^2 surface area would at $E = 1$ TeV detect just one photon per week. All the groups who have attempted observations at these high energies have been relying on Galbraith and Jelley's technique[95,96] of recording the Cherenkov bursts of extensive air showers, first systematically applied in practice by Chudakov *et al.*[97]

The underlying idea of this method is to use an optical photomultiplier system to detect the faint and very brief ($\lesssim 3$ ns) flash of light that accompanies the onset of an extensive air shower. This glow represents the Cherenkov radiation of electrons (or positrons) and is emitted primarily in the same direction that the incident primary particle has been traveling. Such measurements can reveal a discrete cosmic source through comparison of the Cherenkov-burst count rates in the direction toward the suspected source and a small angular distance away from it (representing the cosmic-ray background). Successful observations by the atmospheric Cherenkov technique can be made only on moonless nights, in good weather, and not too far ($\lesssim 45°$) from the zenith.

Table III sets forth the parameters of the Cherenkov detectors with which Cyg X-3 has been observed. To intercompare the observational results one has to allow for certain special features of the different installations, and these are indicated in the table.

Cygnus X-3 was first detected at energies $E \gtrsim 1$ TeV in September 1972 with the facility at the Crimean Astrophysical Observatory.[19,102,103] For the next few years the source was observed in the very high-energy range only by our Crimean group. From 1977 onward Cyg X-3 was successfully monitored at the Lebedev Physics Institute high-altitude station in the T'ien Shan. Then in 1980 the source was reliably detected by the Mount Hopkins group in Arizona (see Table III).

The Crimean program continued through 1980 and a great deal of information on Cyg X-3 was acquired. On the whole these data stem from a quite homogeneous series of measurements, because throughout the 9-yr interval no substantial changes were made in the apparatus[68,69,98,102–109] (apart from a 1974 modification of the observing procedure: a straight scanning operation was replaced by the more effective practice of alternately setting on the source and the background). The most significant outcome of this systematic program was the finding that the γ-ray flux from Cyg X-3 is highly variable. This property seriously impedes comparison of the data obtained with different installations, since the measurements as a rule have not been concurrent.

The outstanding results from the Crimean observations of Cyg X-3 at very high γ-ray energies are:

1. The mean intensity $I(E \geqslant 2\ \text{TeV}) = (1.8 \pm 0.5) \times 10^{-11}$ photon cm^{-2} sec^{-1}. If the source is at 11.6-kpc distance, its luminosity $L_\gamma(E \geqslant 2\ \text{TeV}) = 5\times 10^{36}$ erg/sec.

2. In almost every year of observation the period $P_0 = 4^{\text{h}}.8$ can be identified. Its mean value for 1972–1977 was $0^{\text{d}}.199683(1)$, in perfect agreement with the x-ray value (Table II). Over the 1972–1979 interval the period is estimated[68] to have been lengthening at a rate $\dot{P}_0 = (3.0 \pm 1.4) \times 10^{-9}$, again quite close to the $\dot{P}_0$ value later derived from the x-ray observations (Table II).

3. In the light curve for period P_0 (Fig. 9) there are two peaks[108]: at phases $\varphi = 0.15 - 0.2$ and $0.6 - 0.8$. Possibly the relative amplitude of the two peaks may vary with time: in 1972–1973 the peaks seem to have been nearly equal,[105] but subsequently the first peak became more prominent. At those phases, $\varphi = 0.15 - 0.2$, the mean intensity over the

TABLE III. Observations of Cyg X-3 in the very high-energy range ($E \gtrsim 10^{12}$ eV).

Observing station	Elevation above sea level, m	Optical system	Reception cone, deg	Energy threshold, eV	Count rate, min^{-1}	Interval of observation	Flux density, photon $\text{cm}^{-2}\,\text{sec}^{-1}$	
							Mean value	Peak value
Crimean Astrophys. Ob.[98]	600	4 parabolic mirrors, diam. 1.5 m, $f = 0.65$ m, on separate equatorial mounts	1.8	$2\cdot10^{12}$	80	September 1972–November 1980	$(1.8\pm0.5)\cdot10^{-11}$	$1.3\cdot10^{-10}$
T'ien Shan Station, Lebedev Phys. Inst.[99]	3000	3 parabolic mirrors, diam. 1.5 m, $f = 0.65$ m, on same alt-azimuth mount	3.0	$2\cdot10^{12}$	30	July 1976 – October 1982	$(7.3\pm1.3)\cdot10^{-11}$	$(9.5\pm2.0)\cdot10^{-11}$
Harvard–Smithsonian, Mt. Hopkins, Ariz.[100]	2300	Cellular mirror, diam. 10 m, on alt-azimuth mount	1.0	$1\cdot10^{12}$	—	October–November 1976	$\leqslant 2.1\cdot10^{-11}$	--
Harvard–Smithsonian and Univ. College Dublin, Mt. Hopkins[26]	2300	2 parabolic mirros, diam. 1.5 m	2.0	$2\cdot10^{12}$	—	April–June 1980	$\sim 1{,}5\cdot10^{-11}$	$\sim 1{,}5\cdot10^{-10}$
Solar power, Edwards AFB, Calif.[27]	700	2 heliostat mirrors, diam. 11 m	1.0—1.8	$5\cdot10^{11}$	60	August–September 1981	$\sim 8.0\cdot10^{-11}$	$\sim 4.0\cdot10^{-10}$
Univ. of Durham, Great Salt Lake[101]	1450	4 telescopes each with 3 parabolic mirrors, diam. 1.5 m	1.7	$2\cdot10^{12}$	50	July–October 1981	$9\cdot10^{-12}$	$7.0\cdot10^{-11}$

whole interval of observation was 1.6×10^{-10} photon $\text{cm}^{-2}\,\text{sec}^{-1}$.

4. Occasionally for short intervals (a few days) excess flux was observed at all phases of P_0. Sporadic radiation of this kind was detected, in particular, in September 1973 and August 1974,[106] and also in October 1980.[109]

5. The γ-ray intensity also varies[69] with the same period $P_1 = 34^d.1$ that has been identified in the x-ray[22] and radio ranges.[110] In all cases the intensity minima coincide. Moreover the P_0 light curve depends on the phase ψ of the period P_1 (Fig. 10). The diminished activity[69] of the source in 1976–1979 compared with 1972–1975 could be due to observational selection, in the sense that most of the 1976–1979 observing sessions occurred at "unfavorable" phases[110] ψ.

For the most part the Crimean observations are in good accord with the results from the 5-yr (1976–1980) observing program carried out at the Lebedev Institute station.[99,111]

The 1980 observations of Cyg X-3 jointly, by the Harvard–Smithsonian Center for Astrophysics and University College, Dublin,[26,112] once again convincingly demonstrated the variability of the source: the γ-ray effect essentially was observed only during the first half of the session (late May and June), at a time when the x-ray activity was enhanced. The γ-ray flux was reported to have strengthened at a "favorable" phase of the period P_1, concurrently with a change in the P_0 light curve. In these observations the γ-ray light curve showed a single narrow peak, at phase $\varphi = 0.7$–0.8.

Measurements with a solar-power facility at Edwards Air Force Base in California[27] (threshold energy 0.5 TeV) similarly disclosed only one peak in the P_0 light curve, at

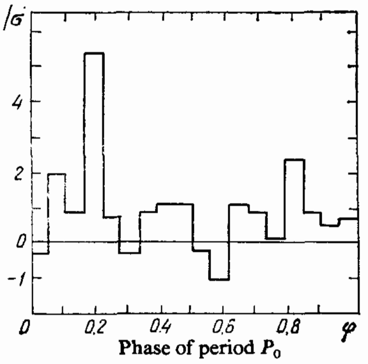

FIG. 9. Light curve of Cyg X-3 for very high-energy γ rays ($E > 2\times10^{12}$ eV), based on the period $P_0 = 4^h.8$ (Neshpor *et al.*[108]). A, mean amplitude of effect recorded; σ, statistical error in amplitude.

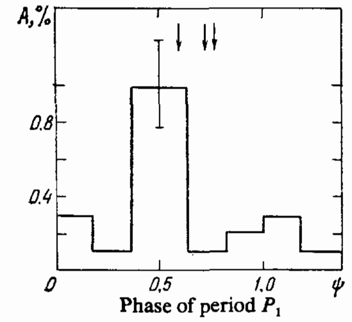

FIG. 10. Intensity of the P_0-periodic component of the very high-energy γ rays as a function of phase of the period P_1 (Neshpor *et al.*[69]). Arrows mark the phases of peak x-ray flux from Cyg X-3.

$\varphi = 0.5 - 0.7$. A light curve of the same kind was obtained from simultaneous 1981 observations by a University of Durham group in Utah,[101] with a higher threshold ($E \geqslant 2$ TeV). There wa some evidence that the γ-ray peak at $\varphi = 0.6$ was modulated with the period P_1.

Taken together, the results described above indicate that in the very high-energy range Cyg X-3 has confidently been detected as a γ-ray source by five separate installations. The values recorded for the γ-ray flux from the source differ considerably (Table III). However, in light of the variable behavior of the source and the notorious uncertainty involved in estimating the energy thresholds of the instruments, the disparities can be explained in a natural way. Although the investigators unanimously believe that the γ-ray flux of Cyg X-3 does indeed vary with the period $P_0 = 4^h.8$, the different series of measurements have yielded distinct light curves: according to the Crimean and T'ien Shan data the curve has a double peak, at phases $\varphi = 0.2$ and $\varphi \approx 0.7$, while the Arizona, California, and Utah observations show just one peak (at $\varphi = 0.5 - 0.7$), differing somewhat in width.

Undeniably the character of the variability of the γ-ray source makes it no simple task to derive the P_0 light curve. In fact the long-term measurements at the Soviet stations indicate that from time to time Cyg X-3 becomes a source of sporadic γ rays: the flux can be comparatively high at any phase φ of the period. How these intensity enhancements are distributed with respect to power (that is, amplitude and duration) remains unknown. Low-power bursts may be quite common (such bursts, or *transients*, may perhaps have been observed by Weeks[113]), but they cannot be discriminated with much confidence and therefore are presumably embedded in the data from which the light curve is constructed. Accordingly the light curve will contain certain distortions, for the measurements during a given observing season most likely will be distributed nonuniformly with respect to φ. It also is a perplexing matter to allow properly for the period P_1 and for the dependence of P_0 light curve on the P_1 phase ψ.

All these difficulties, as well as the selection effect due to the domination of the observing schedule by the phase of the moon, can, one would think, adequately explain why a peak in the P_0 light curve has been detected near $\varphi \approx 0.7$ (although with differing width) by every group of observers, while the $\varphi \approx 0.2$ peak occurs only in the Crimean and T'ien Shan measurements. Quite possibly, as mentioned in Sec. 3d for the high-energy γ rays,[89] at very high energies as well φ may vary regularly with the phase ψ.

In order to learn what mechanism is generating the γ-ray emission, information on its energy spectrum is essential. Here too one meets with considerable difficulty. As we have said, the threshold energy above which a Cherenkov detector will record γ rays is very uncertain (by at least a factor 2). All the data presently available are plotted together in Fig. 11. The points in this graph designate the flux averaged over the period P_0, but they neglect the contribution of the sporadic component and the dependence of the flux on the phase ψ of period P_1. Hence the most reliable and representative points are those which are averages over long intervals: 9 yr of observation in the Crimea (open circles) and 4 yr at the Lebedev T'ien Shan station (open square). These points imply a spectral index of 1.2 ± 0.3.

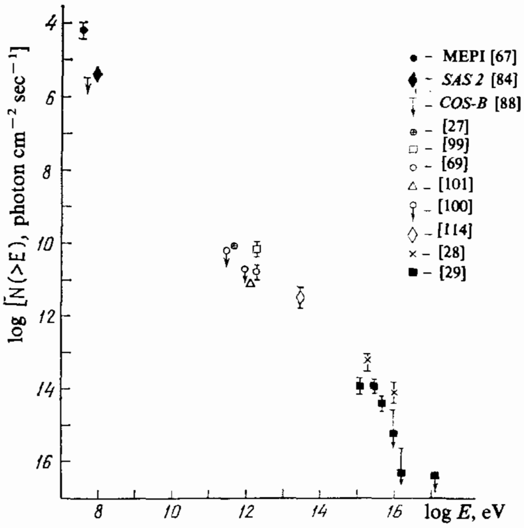

FIG. 11. The integral energy spectrum for the γ rays from Cyg X-3 (reference numbers bracketed; MEPI, Moscow Engineering Physics Institute).

f) Ultrahigh-energy (> 10^{15} eV) γ rays

Very recently some results have been reported for the flux of 10^{15}–10^{16} eV γ-ray photons from Cyg X-3, detected with the apparatus designed to record the charged particles in extensive air showers. These facilities utilize particle counters that can measure the differential in the EAS arrival time at different points to within a few nanoseconds. As a rule each installation comprises numerous counters spread over a sizable area (several square kilometers), so that the delay of the signals in the individual detectors will convey information on how the EAS axis is directed in space.

A convincing result has emerged from an experiment at Kiel,[28] after nearly four years of measurement (1976–1980). Particle arrival directions were measured to 1° accuracy. From the distribution of events with respect to the directions of the incoming primary particles it is clear that a statistically significant excess is present in the direction toward Cyg X-3. Furthermore the showers coming from that direction had characteristics similar to those of showers induced by γ-ray photons. But the most persuasive demonstration that the excess flux is related to the source Cyg X-3 is the finding of a $4^h.8$ periodicity in the EAS records. Indeed the peak in the phase distribution has only 1/50 the width of the period P_0 itself. The authors[28] estimate a threshold energy of 2×10^{15} eV for the γ-ray showers. At $E = 2 \times 10^{16}$ eV the radiation spectrum appears to steepen. The mean flux $I(>2 \times 10^{15}$ eV$) = (7.4 \pm 3.2) \times 10^{-14}$ photon cm^{-2} sec^{-1}. Applying the Pearson criterion, Samorski and Stamm have found a mean period $P_0 = 0^d.1996816(2)$, slightly different from the P_0 based on the measurements of x rays and very high-energy γ rays (Table II).

A similar analysis of EAS measurements with the Haverah Park array in England[29] also has revealed excess flux from the direction of Cyg X-3. These observations too have disclosed a cycle in the γ-ray flux with period P_0. The mean intensity $I(>3 \times 10^{15}$ eV$) = (1.5 \pm 0.3) \times 10^{-14}$ photon

cm^{-2} sec^{-1}. The downward bend in the spectrum at energies above 10^{16} eV is more definite than at Kiel,[28] but unlike the case with the Kiel data the period P_0 agrees perfectly with the latest x-ray results.[66]

Gould[115] has analyzed lthe Cyg X-3 energy spectrum in the ultrahigh-energy γ-ray range. He considers how γ-ray photons will be absorbed in transit from the source to the observer as they interact with photons γ' of the cosmic blackbody radiation to form electron–positron pairs:

$$\gamma + \gamma' \rightarrow e^+ + e^-. \tag{2}$$

The reaction (2) has a threshold energy $E_{\gamma\text{thr}} = 4\times 10^{14}$ eV. Beyond threshold the reaction cross section at first increases sharply, but at $E_\gamma = 2\times 10^{15}$ eV it begins to fall off approximately as $E^{-0.25}$. Since an optical depth $\tau \sim 1$ will build up along the path of the photons, the flux measured in the interval $E_\gamma = (2\text{–}10)\times 10^{15}$ eV ought to be corrected before the true spectrum of the source is determined. The appropriate correction factors turn out to be $K = 3, K = 1.8$ at either end of this energy interval. When so corrected, the Kiel spectrum[28] no longer conforms to a single power law but displays a hump in the 10^{15}–10^{16} eV region. To draw any particular conclusions from this behavior, however, seems premature, in view of the wide scatter of the experimental points at these energies (note the shift between the crosses and the filled squares in Fig. 11).

Stephens and Verma[116] point out that the apparent cutoff in the Cyg X-3 spectrum for $E_\gamma \gtrsim 10^{16}$ eV might come about in the source itself due to pair production in its magnetic field. If $r = 10^{14}$ cm, a field strength of 0.7 gauss would be adequate to account for the falloff observed.

Preliminary evidence has also been obtained for a 34^d cycle in the ultrahigh-energy flux.[28] Of interest in this regard are some results obtained[114] with an EAS apparatus having a comparatively low ($\approx 5°$) angular resolution and a low (3×10^{13} eV) energy threshold. Although a 3σ excess in the Cyg X-3 γ-ray flux was indeed recorded, the most noteworthy finding comes from analysis of the behavior of the P_0 light curve with phase ψ of the $P_1 = 34^d$ day variation.[114] While in one ψ-interval peak flux occurs at phase $\varphi = 0.6 - 0.8$, in another ψ-interval the flux peaks at $\varphi = 0.15 - 0.35$. This same rule probably applies throughout the γ-ray region.[89]

We see, then, that the emission of ultrahigh-energy γ rays is genuine: Cyg X-3 is the first cosmic source from which photons of such high energy are known to have been received. Another important factor is that the ultrahigh-energy range carries great weight in the total radiation from this source. As Fig. 11 indicates, the spectrum extends up to 10^{16}-eV energy with hardly any change and seemingly can be fitted by a unified power law with average spectral index $\alpha \approx 1.0$. The fact that not all the points lie along this line is probably attributable to inaccurate energy thresholds (unfortunately we still lack a good method for absolute calibration of EAS equipment). At ultrahigh energies the luminosity of Cyg X-3 is impressive: even allowing for the cutoff in the spectrum above 10^{16} eV, it amounts to $L_\gamma(E > 2\times 10^{15}$ eV$) = 1.1\times 10^{36}$ erg/sec.

4. MODELS FOR CYGNUS X-3

At the outset Cygnus X-3 was thought to represent a conventional x-ray binary system like Scorpius X-1 or Circinus X-1, perhaps in a late stage of evolution.[117] The first models proposed for the Cyg X-3 source[58,118] relied on this idea. They postulated that $P_0 = 4^h.8$ constitutes the orbital period and that the object itself is a close binary system. Davidsen and Ostriker,[118] in particular, interpreted the x-ray source as a white dwarf accreting material being intensively lost as stellar wind by the other component, a red dwarf star. An extra energy source for the white dwarf would be thermonuclear reactions taking place in the accreted matter on its surface. A system of this kind might have been analogous to the U Geminorum objects, variable stars typified by periodic flares with an amplitude of several magnitudes in visible light. This model would explain the x-ray light curve with period P_0 in a natural way, for the stars' orbital motion would cause the optical depth of the gas between the x-ray source and the observer to vary cyclically. And the same period ought to manifest itself in the infrared, because the gas cloud formed by the stellar wind should be warmest close to the x-ray source.

Such models served as a basis for quantitative interpretations of the radio data. Analysis of those observations indicated above all that the radio waves are of synchrotron origin, and that the outbursts result from the creation of a great many relativistic electrons. The radio intensity variations at different frequencies during an outburst can be reproduced quantitatively under several initial assumptions, although most authors have adhered to the same qualitative picture: an expanding cloud of relativistic electrons moving in a plasma with a magnetic field. The rather primitive idea of the accelerated electrons undergoing only adiabatic cooling[10,57] will not work, as more detailed calculations demonstrated.[119] A much better fit to the observations is obtained if one allows for the bremsstrahlung losses of the electrons in the plasma[120,121] or for their synchrotron losses.[122] One can also satisfy the observations of the September 1972 outbursts to good accuracy by permitting a nonlinear expansion of the cloud (the dynamical model[123]) or by supposing that outbursts follow one another at quite short intervals (the colliding shock-front model[124]).

Following the general approach of Davidsen and Ostriker,[118] Seaquist developed a comprehensive model to explain the chief properties of the radio outbursts.[125] Relativistic electrons would be accelerated by shocks resulting from nuclear explosions of material being accreted onto the white dwarf surface. According to Seaquist the character of the radio flare would depend significantly on the environment in the stellar wind and on the explosion parameters: if the explosion is strong enough, it would sweep away much of the gas and the shock producing the next outburst would propagate through a more rarefied medium. Calculations allowing for the electrons' loss of energy to adiabatic cooling, bremsstrahlung, and synchrotron radiation furnished estimates for several parameters of the binary system. For example, at a distance $r \approx 10^{14}$ cm from the center of the system the plasma density would be $\approx 10^7$ cm^{-3} and the magnetic field strength, ≈ 0.1 gauss. Electrons of 10^8-eV energy would be injected at $r \approx 10^{11}$ cm. Similar estimates were obtained[126] by analyzing the quiescent radio emission of the source. If the accelerated electrons have a power-law energy spectrum of form E^{-2}, the magnetic field strength would fall off with distance as $H(r) \propto 1/r$, corresponding to the geometry of an Archimedean spiral.

But not all the radio data could be accommodated by the foregoing models. Thus, the nature of the quasiperiodic fluctuations in radio intensity remained unclear,[127] nor was there any explanation of the period $P_1 = 34^d$ shown by the radio emission.[110]

Returning to the efforts to devise a synthetic, self-consistent model of the source, we would emphasize that there still is no irreproachable proof that P_0 represents an orbital period. Syunyaev[128] once suggested that P_0 be regarded as the rotation period of a pulsar; the orbital period should then amount to several years. In such a model the x-ray luminosity of the source would be due to the accretion of gas arriving from the companion star, a supergiant.

Milgrom[129] accepted P_0 as the orbital period and regarded the compact object as accreting material from a normal main-sequence star, but suggested that the system is embedded in a gaseous envelope that absorbs and reemits the x rays emanating from the pulsar (a "cocoon" model). The cocoon would have a characteristic size of $\approx 10^{12}$ cm and its gas density would be $\approx 10^{13}$ cm^{-3}. So dense an envelope would prevent us from observing lthe x-ray pulsations due to the spin of the pulsar (with a period of order 1 sec). The P_0 light curve would correspond to the shadow of the normal star on the envelope. This cocoon model requires that the pulsar have an exceptionally high x-ray luminosity, $L\,(>25$ keV$) = 6\times 10^{38}$ erg/sec, two orders above that of the standard x-ray pulsars.[70] How the cocoon itself might have originated was not explained.

Today all these models evidently are just of historical interest, for they have proved to be based on an incorrect idea: Cyg X-3 decidedly is not a typical accreting x-ray binary system. To suppose that it is would contravene several well-established facts that cannot be interpreted by any of the models outlined above:

1. Far more radio emission is coming from the source than is observed in an x-ray binary. Even when Cyg X-3 is quiescent, the ratio of its radio to its x-ray flux is two orders greater than observed in the typical x-ray binary Sco X-1.

2. During radio outbursts the energy that Cyg X-3 releases simply through its relativistic electrons greatly surpasses the energy of a typical flare in U Gem–class sources.

3. Cyg X-3 is a powerful source of γ rays ranging from 10^8 to 10^{16} eV, something not observed in ordinary x-ray sources.

Since the only galactic objects known to emit γ-ray photons are young pulsars, models regarding one component of the binary system as a young pulsar receive considerable support. The suggestion that Cyg X-3 might contain a young ($\approx 10^2$ yr old) pulsar was first put forward by Basko *et al.*[130] (see also Treves,[131] who proposed that P_0 might be the precession period of the axis of a rapidly spinning object). Subsequently Bignami *et al.*[132] worked out more fully the hypothesis of a young pulsar in the Cyg X-3 system, taking P_0 as the orbital period and regarding the companion star as a red dwarf.

The lack of the radio-emitting supernova envelope that we ought to observe if the pulsar is indeed young (10^2–10^4 yr old) was attributed[133] to the neutron star (the pulsar) having formed through nonexplosive collapse. The energy going into the high x-ray power ($\approx 10^{38}$ erg/sec) of the source would be drawn from the pulsar's rotational energy. Abrupt changes in the pulsar spin period ("glitches"), such as often observed in young pulsars, would accompany the radio outbursts. Gas enshrouding the system in a cocoon-like envelope would be emitted by the red dwarf, whose atmosphere would be strongly heated by the relativistic wind from the pulsar. This relativistic wind would accelerate the gas and eject it from the system, which would be losing mass at an average rate of $\approx 10^{-6}\, M_\odot$/yr. Upon encountering the gas the pulsar wind would form a shock front with disordered magnetic and electric fields, and that is where the particles—electrons and protons—would be accelerated.

Gamma rays of $\approx 10^8$-eV energy would be produced by the synchrotron radiation of electrons in 10^2–10^3 gauss magnetic fields frozen into the gas, as well as through nuclear interactions of the accelerated protons with the gas atoms. On the basis of the energy density of the relativistic wind Bignami *et al.*[132] estimated the gas to have a temperature $T \approx 10^7$ K. However, in this model the infrared radiation of the source would represent primarily the nonthermal synchrotron component. The P_0 light curve would result from eclipses of the brightest portion of the gas by the star; the phases φ should coincide for radiation at all frequencies from the infrared to the γ-ray range.

In a general way this model does offer a good description of much of the observational evidence, even such features as the aperiodic x-ray variations. But Bignami *et al.* did not consider the very high-energy region at all; indeed it is far from clear how the model can account for the presence in the spectrum of photons with energies $E_\gamma > 10^{12}$ eV.

Several other versions of the model have been proposed,[134–138] with a pulsar and a dwarf star. Fabian *et al.*[134] have suggested that the $\approx 10^8$-eV emission results from the inverse Compton scattering of pulsar-accelerated electrons by the x-ray photons. Estimates indicate that the infrared radiation should be of synchrotron origin. The γ-ray emission would be modulated by the period P_0, regarded as the orbital period, because of the anisotropy of that radiation.

One of the present authors[135] has pointed out certain parallels between the radiation spectral of Cyg X-3 and the Crab Nebula over a very broad range of frequencies. The analogy supports the idea that Cyg X-3 contains a pulsar $\approx 10^2$ yr old. Gamma-ray photons up to the very high-energy range would result from bremsstrahlung of the electrons in the gas surrounding the system. Radio and infrared data have been utilized to estimate the relativistic-electron, plasma, and magnetic field densities in the cloud. These results[135] should be regarded as grossly provisional, since they rely on the crude premise that the radiation in different parts of the spectrum is all generated within the same volume.

Tsygan[136] has noted that the pulsar in Cyg X-3 might be

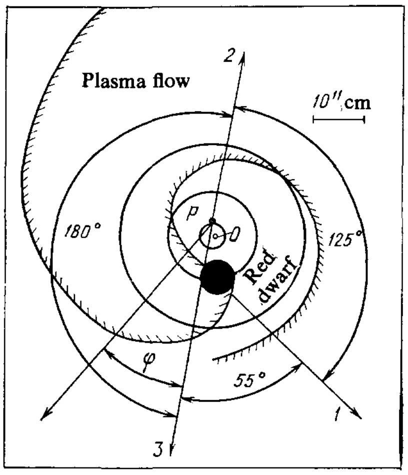

FIG. 12. Diagram of the Stepanyan model[140] for the source Cyg X-3. P, pulsar; O, center of mass of binary system; φ, angle between line of sight and axis of system. 1) Direction of minimum x-ray emission; 2) direction of maximum x-ray emission; 3) direction of maximum emission of very high-energy γ rays ($E_\gamma \gtrsim 10^{12}$ eV).

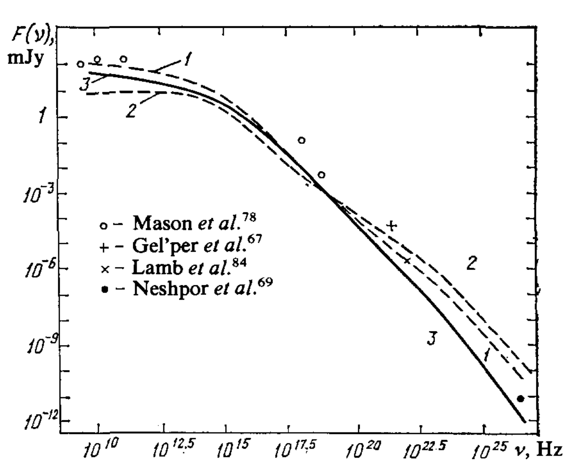

FIG. 13. Comparison of theoretical radiation spectra[140] against the flux densities observed for Cyg X-3. 1) Magnetic field strength $H = 100$ gauss at surface of red dwarf; 2) $H = 10$ gauss; 3) the case of zero losses to inverse Compton scattering.

young in an evolutionary rather than a chronological sense if its magnetic field is no stronger than 5×10^{10} gauss. In this event the requisite high luminosity of the system could be achieved for a pulsar with a 4-msec spin period, some 10^5 yr old. The issue of the unobserved supernova envelope in Cyg X-3 would accordingly be resolved. Interestingly enough, a pulsar with a period even shorter than this, 1.5 msec, has recently been discovered,[139] and it is indeed $\approx 10^5$ yr old.

Apparao[137] has remarked that the data on the 10^8-eV emission of Cyg X-3 can be reconciled with the radio results if one assumes that the γ-ray photons are produced through Compton scattering of the radio-emitting electrons by thermal x-ray photons of $\approx$1-keV energy. And Milgrom and Pines[138] have modified the earlier cocoon model: embedded in the cocoon envelope, which as before would be responsible for the x-ray light curve, there would lie a pulsar spinning with a period of 10 – 30 msec.

Another model essentially very similar to that of Bignami *et al.*[132] was proposed by one of us[140] in 1982, and is illustrated schematically in Fig. 12. A red dwarf companion would shed gas, which would escape from the system by centrifugal force due to the orbital motion, forming a gaseous spiral with a magnetic field frozen into the plasma. The particles accelerated by the pulsar would have an $E^{-2.2}$ energy spectrum in the 10^9–10^{16} eV range. Traveling radially outward, they would impinge on the magnetic field, whose strength would be 10 – 100 gauss at the surface of the dwarf star. Over the whole frequency range the density of synchrotron-radiation photons would be so high that the energy losses to inverse Compton scattering would be expected[140] to predominate over the synchrotron losses for particles as energetic as 10^{14} eV.

The most distinctive feature of this model is that it entails calculations both of the electromagnetic-radiation spectrum and of the particle energy spectrum, with the system of kinetic equations for the particles and the radiation field being solved. Figure 13 plots several alternative radiation spectra for Cyg X-3 obtained from these numerical solutions. Covering the full frequency range studied, the spectra, as one can see, fit the experimental data quite well. At x-ray energies, in the middle of the diagram, the measured flux is somewhat higher than predicted because most of the x rays represent thermal emission of heated gas ($T = 10^7$–10^8 K). The pulsar would convey to the accelerated particles a total power of 2×10^{38} erg/sec, about the same as in the case of the Crab Nebula pulsar.

Calculations have also been performed[140] to establish the γ-ray light curves. The model nicely explains the P_0-phase correlation between the minimum x-ray flux and the peak γ-ray emission. Admittedly, the model gives no interpretation of the second peak, at $\varphi = 0.6 - 0.8$; but it is pertinent to mention that at ultrahigh energies ($E_\gamma > 10^{15}$ eV) the light curve evidently has just one peak,[28,29] coincident in phase with the first peak ($\varphi = 0.2 - 0.3$) in the very high-energy range. Presumably the ultrahigh-energy photons are of synchrotron origin. The peak at $\varphi \approx 0.6$ would then evidently be attributable to inverse Compton scattering.

Still another model, relying on the very high-energy results, has recently been suggested by Vestrand and Eichler.[141] As in most of the earlier models, P_0 is interpreted as the orbital period. The authors consider a light curve comprising two peaks separated in phase φ by $0.4P_0$. This shift would result from the accelerated-particle source, the pulsar, being eclipsed by the secondary component of the binary system. Of the possible mechanisms for generating γ rays as the charged-particle beam passes through the stellar atmosphere, the greatest contribution to the measured flux will come from electron bremsstrahlung and pion decay. Vestrand and Eichler remark that with the prevailing geometry of the system, particles can be shock-accelerated (as in the model of Bignami *et al.*.) only to energies of order 10^{14} eV. Thus if photons of still higher energy were to be detected, one would have a counterargument to this mode of acceleration. But as we have seen in Sec. 3f, γ rays of energy $E_\gamma = 10^{15}$–10^{16} eV do indeed occur in the emission of Cyg X-3, implying, if the model[141] is correct, that the particles are accelerated not by a shock propagating from the pulsar to the companion star but directly in the pulsar itself.

We would emphasize that there still is no conclusive proof that Cyg X-3 does contain a young pulsar. In particular, searches for very short (millisecond) periods have not yet yielded a definite result.[142] On this basis some authors have proposed that the compact object in the Cyg X-3 binary system might be a black hole. Two models in this vein put forward several years ago[143,144] should now be set aside, as both firmly predict that the γ-ray spectrum will cut off in the very high-energy range, contrary to observation.

Since the γ-ray light curve of Cyg X-3 somewhat resembles the x-ray curve of the object SS433, Grindlay[145] has suggested that the two sources may be similar in nature, each representing a binary system with a black hole of $\approx 10\,M_\odot$. In that event Cyg X-3 ought to contain subrelativistic gas streams like those observed in SS433. It is in these streams, Grindlay maintains, that the electrons would be accelerated to extremely high energies. Subsequently the electrons would release their radiation in a cocoon surrounding the system (or, in the case of SS433, in the supernova envelope), generating the γ-ray flux observed. On this interpretation the period $P_1 = 34^d$ would represent the precession period of the accretion disk, while $P_0 = 4^h.8$ should be the orbital period. These arguments would carry more conviction if SS433 should turn out to be a γ-ray source (in fact a flux of very hard γ rays from this object is now suspected). Moreover the hypothesis that P_1 is the accretion-disk precession period will have to be reconciled with the x-ray data.

Summing up this survey of theoretical models for Cyg X-3, we are prompted to remark that the very richness of assorted ideas, proposals, and hypotheses suggests that in many respects the nature of this source remains a puzzle. No one has yet developed a model that can accommodate all the observational evidence on the radiation spectrum. Probably the main reason is that no indisputable analog of Cyg X-3 has been discovered in the Galaxy. We therefore still do not know its astrophysical status—its evolutionary precursors, its origin and future fate. One object somewhat reminiscent of Cyg X-3, as Gregory and Taylor[146] have pointed out, is the variable radio source GT0236 + 610, which similarly has produced strong radio outbursts. Notably, its position coincides, to within the errors, with the discrete γ-ray source CG135 + 1 in the *COS-B* catalog.[94] Finally, according to the Vestrand–Eichler model[141] the population of objects comparable to Cyg X-3 should be meager indeed—perhaps ten in the whole Galaxy.

5. CONCLUDING REMARKS

Cygnus X-3 is a unique object. It differs sharply, above all in its radiant power, not only from other known discrete sources of γ rays but also from typical x-ray sources in close binary systems. Its intensive radio and γ-ray emission highlights the importance of energetic particles in the lifestyle of this source. There is no resemblance at all to conventional x-ray binaries, all of whose high-energy processes involve accretion onto a compact object, either a neutron star or a black hole. In Cyg X-3, on the contrary, the primary role is played by an acceleration mechanism that shifts the spectrum of the interacting particles toward higher energies. It would seem very reasonable in this regard to suppose, as more and more theorists are doing, that the Cyg X-3 system contains a young pulsar. All the behavioral peculiarities, the high power of the source, and indeed its uniqueness would then be attributable to a neutron star so youthful that, with a 1–10 msec spin period (not yet detected) and a surface magnetic field of 10^{12}–10^{13} gauss, it could act as an efficient accelerator of charged particles.

New observational data will clearly be needed if an adequate model is to be developed for Cyg X-3. At radio frequencies it remains an urgent matter to measure the polarization and its fluctuations with time, particularly at high ν when the source is quiescent. In the infrared it would be invaluable to have data on the slope of the radiation spectrum and to learn whether the spectral index depends on the phase of the period P_0. Such information would help answer the question of the emission mechanism in this spectral region.

Additional and more accurate data on the variability (both periodic and aperiodic) of the x-ray spectrum would also be very welcome. Data of this kind are vital for deciding the nature of the periodic (P_0, P_1) intensity variations. Observations in the hard x-ray range (up to 100 keV) would be especially useful for ascertaining the contribution of nonthermal radiation. We must acquire data on the spectrum (and, of course, its variations) at these energies in order to tie in the x- and γ-ray measurements with each other.

If we are right in supposing that the source contains a young pulsar, then it ought to be producing annihilation γ rays at $E_\gamma = 0.5$ MeV. A detection of the 0.5-MeV annihilation line would be extremely valuable for establishing the true nature of the source. At higher γ-ray energies, of order 100 MeV and 1 TeV, further information on the energy spectrum and its P_0, P_1 phase dependences would be helpful. And finally, in the ultrahigh-energy region, above 1000 TeV, we need to determine at just what energy the γ-ray spectrum of the source cuts off, and to obtain accurate data on its slope and variations.

Thus future research on Cyg X-3, perhaps the most interesting source in the Galaxy, will continue to face quite enough problems fully to occupy the next generation of telescopes and astrophysicists.

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