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An Astronomical Puzzle Called Cygnus X-3

The early history of an x-ray, infrared, cosmic ray, and radio emitting star system.

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Before the summer of 1972 the name Cygnus X-3 "merely" identified one of the compact x-ray sources in the constellation of Cygnus. Now this name, usually abbreviated Cyg X-3, represents a presently unique x-ray, infrared, radio, and cosmic ray source in what is probably an unusual double star system. It was the search for and subsequent study of radio emission from Cyg X-3, aided by a spectacular application of serendipity, that revealed that it could temporarily become one of the strongest compact radio sources in the sky. This discovery has led to what may have been more investigation of a single object, by more astronomers, in a shorter period of time, than ever before in astronomy. Astronomers now are asking, what natural phenomena, occurring in a double star system containing what may be a neutron star or black hole, can turn this system on the far edge of our galaxy into a cosmic accelerator for just a day or two, causing some 10^{49} electrons and presumably protons to be ejected with relativistic energies? In addition, why is such a large-scale phenomenon inoperative most of the time in Cyg X-3, and does it occur often in other objects without our noticing it? These are some of the many intriguing questions posed by the x-ray, infrared, and radio behavior of Cyg X-3.

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Cyg X-3 as an X-ray Source

Cyg X-3 was first discovered as an x-ray source by Giacconi *et al.* (*1*) during a survey of the Cygnus region made with an x-ray instrument on an Aerobee rocket launched in 1966. The most notable feature of Cyg X-3 at that time was the prominent low energy cutoff of the x-ray spectrum (*2, 3*). The spectrum (*3*) is shown in Fig. 1 together with the theoretical curves for two models: a blackbody source with a temperature of 2×10^7 °K, but without attenuation at low energies, and a thermal bremsstrahlung source with a temperature of 7.4×10^7 °K, but and substantial low energy attenuation. The latter interpretation was believed (*2*) to be most likely, with the low energy absorption being blamed on absorption by the interstellar gas between Cyg X-3 and the earth. It was first estimated (*2*) that the amount of absorption corresponded to a line of sight column density of hydrogen of 3×10^{22} atoms per square centimeter. Other x-ray observations have indicated (*4, 5*) that more than 10^{23} atoms per square centimeter are needed. Such large column densities indicated that Cyg X-3 is at least several kiloparsecs (1 parsec $= 3.08 \times 10^{18}$ cm) from the earth.

Following the radio outbursts of Cyg X-3 in September 1972, the x-ray data for this source were subjected to considerably more scrutiny than before. The x-ray satellite Uhuru had been periodically observing Cyg X-3 during the time of the radio outbursts. Early analysis (*5*) of part of the x-ray data showed no signs of x-ray flaring in Cyg X-3 at the time of the radio outbursts. However, when all available data were examined it was found (*6*) that Cyg X-3 was emitting at roughly twice its normal x-ray flux the day before the radio outbursts were detected, at a time when no radio data were being taken.

It was also discovered (*5, 7*) that the x-ray flux from Cyg X-3 normally varied sinusoidally with a period of 4.8 hours. The 4.8-hour periodicity suggests that Cyg X-3 is associated with a double star or binary system with this period; the observed variations would then be produced by an eclipsing of occultation phenomena.

In addition, variations observed in the low energy x-ray cutoff of Cyg X-3 (*6*) correspond to changes in the hydrogen column density from 3×10^{22} up to 2×10^{23} atom cm^{-2}. While there may be 3×10^{22} atom cm^{-2} in the interstellar gas between Cyg X-3 and the earth, the changes are most likely due to variations in the intrinsic x-ray emission of the source or in absorbing gas near the source.

Cyg X-3 as an "Ordinary" Radio Star

Since 1970 considerable effort has been made to find radio counterparts of compact x-ray sources. These searches began after it was discovered that Scorpius X-1, the strongest x-ray source in the sky (besides the sun), was associated with a variable radio source (*8*) with unusual properties. A radio source variable by as much as a factor of 2 in hours was coincident with the star identified with the x-ray source, and this radio and x-ray star was surrounded by a double radio source such that all three sources lay on a straight line, a phenomenon common in radio galaxies and quasars.

In addition to being intrinsically interesting as radio sources, radio counterparts of x-ray sources provide important positional information. Since x-ray source positions usually have rather large uncertainties, the detection of an unusual radio variable inside an x-ray "error box" could be taken as prima facie evidence that the x-ray source had been located, but with positional accuracy down to a fraction of an arc second. With this technique the interferometer of the National Radio Astronomy Observatory (NRAO) in West Virginia and the Westerbork array in the Netherlands have detected radio counterparts of the x-ray sources Cyg X-1 (*9, 10*), GX17 + 2 (*9*), Cyg X-2 (*11*), and, of greatest interest to us at the moment, Cyg X-3 (*12*).

The Cyg X-3 radio counterpart was first detected with the Westerbork array at a frequency of 1.415×10^9 hertz (1.415 Ghz). These and subsequent observations with the NRAO interferometer at 2.695 and 8.085 Ghz (*13, 14*) established that Cyg X-3 was usually a radio source at the level of a few tenths of a flux unit [1 flux unit (f.u.) $= 10^{-26}$ watt per square meter per hertz] with a variability of up to a factor of 2 or so on a time scale of hours. This made Cyg X-3 the strongest of the known radio counterparts of x-ray sources, but not so strong that it was anything but a very faint object in the radio sky.

The early radio data on Cyg X-3 were such that the nature of the radio emission mechanism could not be definitely established. However, it was noted (*15*) that the only other well-studied radio source in the sky that behaved like Cyg X-3 was the radio star Algol, a triple star system 27 parsecs away and easily visible as a second magnitude star.

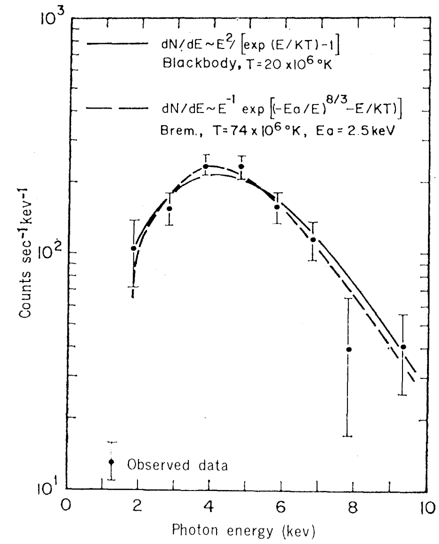


Fig. 1. X-ray spectrum (*3*) of Cyg X-3 in terms of observed counts per second per kilovolt (dN/dE) as a function of photon energy (E). Also shown are theoretical curves for a blackbody source and a bremsstrahlung source (cutoff energy E_a) that fit the data. The Boltzmann constant is K.

Cyg X-3 the Weak Becomes Cyg X-3 the Very Strong

Serendipity is one of the most helpful allies of the astronomer, and the events of August and September 1972 provided another example of this. The first episode in what has become one of the most intensively studied series of events in a radio source began on 30–31 August 1972, when coordinated radio (*14*) and x-ray (*16*) observations of Cyg X-3 found that in the x-ray region it was so weak as to be below detection limits, while at radio frequencies it was present but weaker than ever observed before (or since): 0.01 f.u. Figure 2 shows the time-dependent behavior of the Cyg X-3 radio source at 2.695 and 8.085 Ghz at that time.

With normal human lack of prescience, astronomers were not observing Cyg X-3 at radio wavelengths between 31 August 0800 and 2 September 2000 universal time (U.T., which is the same as Greenwich mean time), but serendipity fortunately intervened.

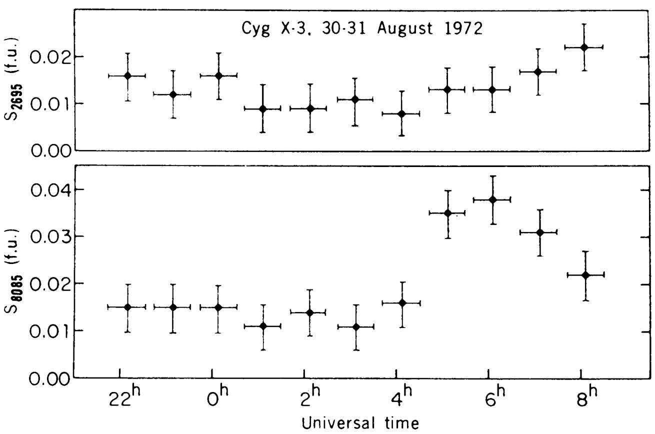
On 2 September 1972 radio observations of the star Algol were begun simultaneously by a group of Canadian astronomers (*17*) using the 150-foot antenna at Algonquin Park in Canada, operating at 10.5 Ghz, and a group of American astronomers (*14*) using the NRAO interferometer, operating at 2.695 and 8.085 Ghz. On the evening of 2 September P. C. Gregory of the Canadian group found himself waiting for Algol to rise above the horizon and decided to take a peek at Cyg X-3 to "see what it was doing." The result was unprecedented—Cyg X-3 appeared to be such a strong radio source that the instrumental gain had to be reduced to allow a proper measurement. When this was done Cyg X-3 seemed to measure 21 f.u. at 10.5 Ghz. This made Cyg X-3 appear to be one of the strongest point sources in the radio sky. Such circumstances quickly caused the suspicion that the equipment was not working properly. Knowing that the NRAO group was preparing to observe Algol, Gregory quickly telephoned them asking in words to this effect, "Would you believe Cyg X-3 at 20 f.u.?" Within moments the NRAO interferometer was finding Cyg X-3 to be about 10 f.u. at 2.695 Ghz and about 18 f.u. at 8.085 Ghz. Thus began an unprecedented international campaign to study Cyg X-3.

Figure 3 shows the time variation of Cyg X-3 at 8.085 (*14, 18*) and 10.5 (*17*) Ghz on the night of 2–3 September 1972. At 2345 U.T. on 2 September Cyg X-3 reached its peak at 22 f.u. at 10.5 Ghz and 20 f.u. at 8.085 Ghz. At this time it was a factor of 2000 stronger than it had been on 30–31 August. During the next 10 hours the radio emissions at the two frequencies varied up and down together, peaking again at 0600 U.T. on 3 September at 21 f.u.

Cyg X-3, the Most Intensively Studied Source

As Cyg X-3 was rising to its first and highest peak on 2 September 1972 there was considerable discussion over the phone between Gregory and myself. Our first idea was that this might be the radio equivalent of a supernova—the rare but well-known event where a collapsing star explodes with such energy and brilliance that it can temporarily shine as bright as an entire galaxy of stars. We therefore immediately decided that everyone possible should be notified by telephone, and that we would ask everyone to pass on to others the name Cyg X-3, the information about the event, and the exact coordinates of the radio source (*13*).

Very soon Cyg X-3 was being observed by the interferometer at the California Institute of Technology at 1.42 Ghz (*19*), the Haystack antenna in Massachusetts at 15.5 Ghz (*20*), the 85-foot antenna at the University of Michigan at 8.085 Ghz (*18*), the 300-foot antenna at NRAO at 2.695 Mhz (*21, 22*), the millimeter-wavelength antenna of Aerospace Corporation in California at 80 Ghz (*23*), and the 48-inch Schmidt camera and 200-inch telescope at Mount Palomar, California, at optical wavelengths (*24*). In the midst of all the excitement, with telephone calls crisscrossing the North American continent, many places that should have been called were inadvertently neglected. One radio astronomer in the Netherlands was reached



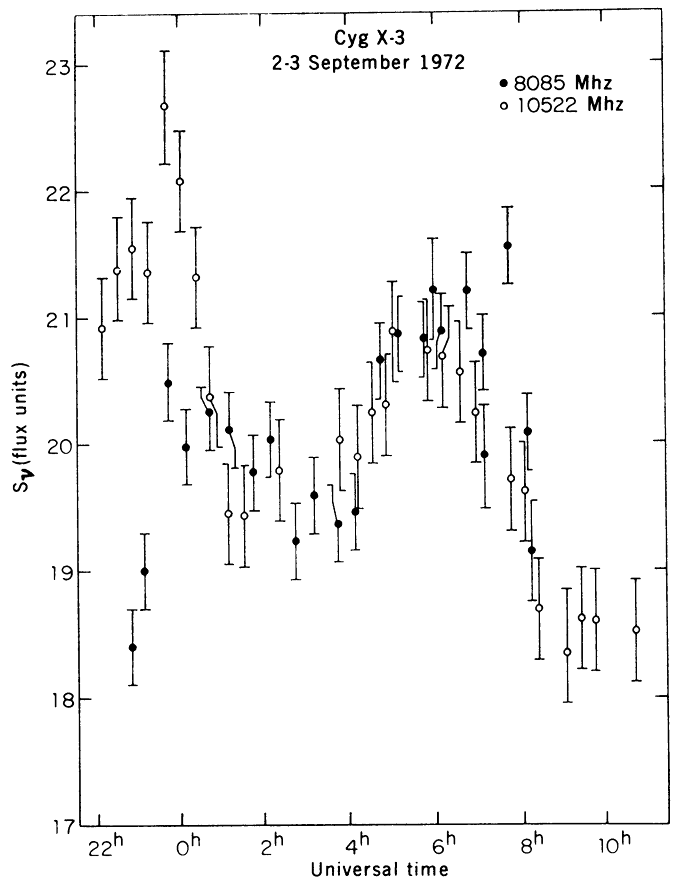


Fig. 2 (left). Cyg X-3 radio flux densities (S) in flux units (f.u.) at 2.695 and 8.085 Ghz on 30–31 August 1972 plotted as a function of time (*14*). Fig. 3 (right). The beginning of the unprecedented radio outburst of Cyg X-3 as observed on 2–3 September 1972 at frequencies of 10.5 (*17*) and 8.085 (*14*) Ghz.

and asked to notify all the European observatories so that they could observe Cyg X-3 as it rose over their horizon. Eventually many astronomers observed Cyg X-3 on the basis of fourth- or even fifth-hand information. More than a hundred individuals and dozens of observatories, including a few x-ray satellites (*5, 7, 25*), became involved in observing Cyg X-3 during the week following 2 September.

One of the topics discussed over the phone between Gregory and myself the night of 2 September was, now that we had tried to get everyone involved in observing Cyg X-3, how should the problem of putting the information together and getting it published be handled? It was obvious that no two people would agree on what should be done, but it was felt that the results should appear as soon as possible because it was hard to tell where these studies might lead. It was therefore decided that as other people were informed about Cyg X-3 they should also be asked to write independent papers describing their own results and to submit them to *Nature*, and that we would ask the editors of *Nature* if it would be possible to publish them all together. In the following days the editors agreed with this plan. The majority of those involved in observing Cyg X-3 during the first weeks of September 1972 agreed to the plan, with the result that the editors were deluged with papers of assorted lengths and content. Eventually the discovery

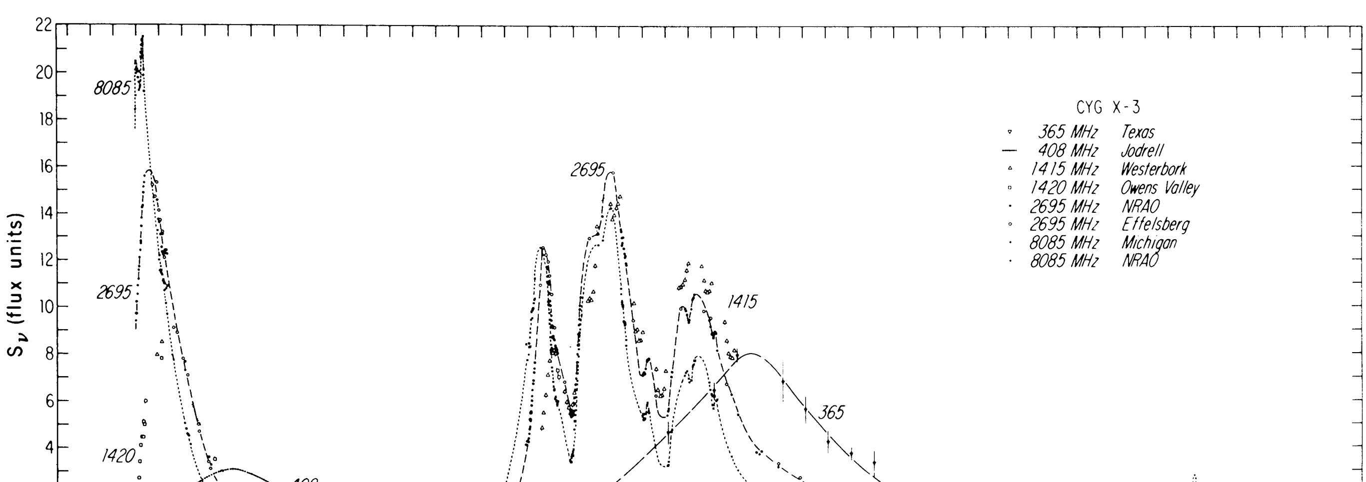


Fig. 4. Events of Cyg X-3 in September and October 1972. Radio flux densities measured at five frequencies by eight observatories are plotted as a function of time. The lines are meant only to sketch the continuity of the variation at each frequency.

papers of the Canadian (*17*) and NRAO groups (*14*) appeared in the 20 October issue of *Nature*, and 21 papers appeared in a special Cyg X-3 issue of *Nature Physical Science* on 23 October. In this first burst of publication there were 23 papers involving 91 authors. A large number of other papers eventually appeared, mostly in *Nature.*

Cyg X-3 as a Radio Source during September and October 1972

It is impossible to fairly describe all the radio data gathered on Cyg X-3 during September and October 1972 without writing a book. However, there were a number of radio frequencies for which the coverage was most extensive during that time period, and for which the data have been published. In Fig. 4 the extensive radio measurements at 8.085 (*14, 18, 26*), 2.695 (*14, 22, 26, 27*), 1.4 (*19, 26, 28–30*), 0.408 (*30*), and 0.365 (*31*) Ghz are plotted as a function of time, together with smooth curves connecting data for the same frequencies. As can be seen from Fig. 4, the radio peaks of 2–3 September at the highest frequencies were preceded by rises where higher frequencies were strongest and were followed by steady decay of a radio source strongest at the lower frequencies (nonthermal). The lower the frequency the lower the flux levels reached, and the more delayed was the peak in time. This behavior is the signature of a synchrotron radiation event in which relativistic particles are ejected in an expanding region of relativistic particles and coupled magnetic fields; the radio emission is produced by interaction between the cosmic ray electron component and the magnetic fields, with the particles rapidly losing energy. Such phenomena are familiar in quasars, although in quasars such events have time scales of years, whereas the first Cyg X-3 event had a half-life of a little more than a day. The most significant result of the identification of the Cyg X-3 event of 2 to 13 September as a synchrotron radiation event is the conclusion that Cyg X-3 is capable of ejecting bursts of cosmic rays in copious amounts for short periods of time.

An obvious question being posed in the middle of September 1972 was whether such radio outbursts were common. A partial answer came when a second and rather different series of Cyg X-3 events began on 18 September. A number of observatories were routinely monitoring the radio behavior of Cyg X-3, so these events were caught early and their complexity was fairly well recorded.

Up until 21 September the second Cyg X-3 event appeared to be a similar, but less intense, version of the event of 2 to 13 September. The increase in radio flux looked like a typical rise from a self-absorbed source which reached a peak on 20 September, then began a decay as a relatively transparent nonthermal synchrotron event. However, the decay was interrupted on 21 September by a reenergization of the source, which appeared to produce two broad, major peaks at the high frequencies during the next week. As can be seen in Fig. 4, only the 365-Mhz curve (*31*) shows a single rise and decay. Because the third and fourth peaks show no significant signs of self-absorption, and show only small variations on short time scales, the general interpretation is relatively simple. The expanding "bubble" of coupled relativistic particles and magnetic fields that was observed from 18 to 21 September largely swept away the magnetic fields in the vicinity of the cosmic ray source. Thus, particles ejected in later events expanded in relatively field-free space until they caught up with the more slowly expanding bubble containing magnetic fields associated with the first ejection (18–19 September). The increased supply of cosmic ray electrons in a relatively large volume produced a transparent nonthermal source that increased and then decreased its strength under the influence of both a variable resupply of cosmic rays and the usual energy loss mechanisms. After roughly 27 September the major resupply ceased, and the normal decay due to energy losses more or less proceeded. The 365-Mhz variations are then of particular interest because the source remained self-absorbed all during the major ejection events and merged together on about 29 September to produce one peak at 365 Mhz, which then decayed away.

Thus, the four major peaks observed at the higher radio frequencies represent four successive periods during which Cyg X-3 succeeded in ejecting relativistic particles or cosmic rays. The short time scale variations seen in Figs. 3 and 4 are probably due primarily to fluctuations in the cosmic ray ejection, but in some cases also to inhomogeneities in the strength and structure of the magnetic fields that must be present to produce the radio source. The most striking short time-scale variations appear as quasi-sinusoidal modulations of the radio flux, particularly at 8.085 Ghz for the peak on 2–3 September, 25 September, 26–27 September, and 27–28 September, with lesser examples also occurring. Strikingly, the minima

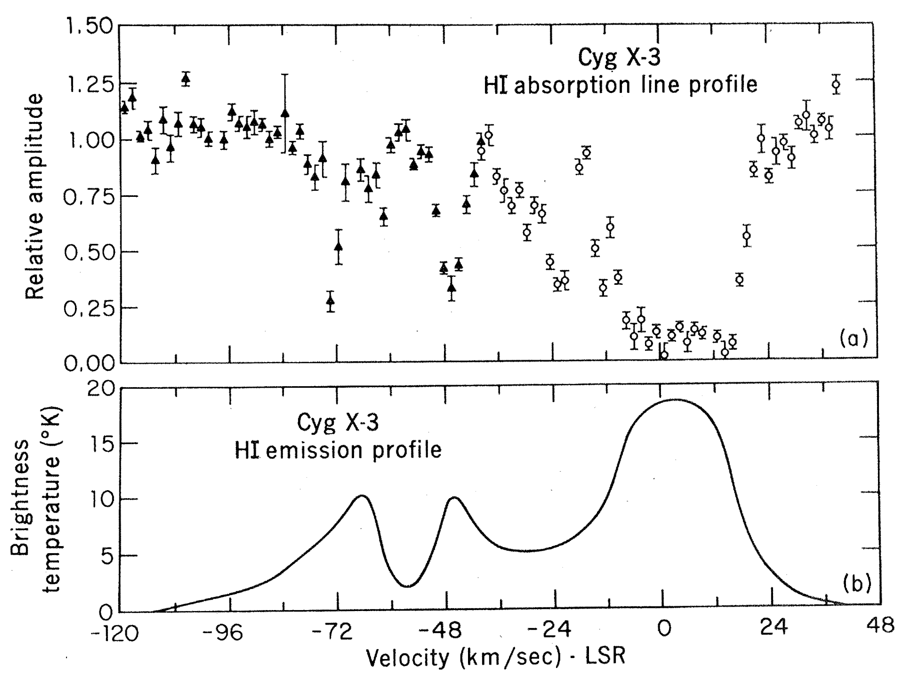


Fig. 5. (a) HI absorption line profile measured by Chu and Bieging (*29*) on 21 September 1972 and (b) emission line profile for this region of the sky. Both are plotted against velocity with respect to the local standard of rest (*LSR*).

and maxima for this modulation seem to appear with a periodicity of 0.5 or 1.0 day.

Among the radio observations that could be made during the Cyg X-3 outbursts a few are of particular interest. At least three major efforts (*27–29*) were made to measure the absorption in the radio spectrum due to neutral hydrogen (HI) in the line of sight to the source. The most detailed results were obtained with the Caltech interferometer by Chu and Bieging (*29*), who made a very sensitive absorption measurement exactly at the 1.42-Ghz peak on 21 September 1972. Their absorption spectrum and the associated HI emission profile for this region are shown in Fig. 5. It is well established that the three major bumps in the HI emission profile are due to emission from gas in three different regions: (i) the broad bump near 0 velocity is due to gas in the local region of the spiral arm of our galaxy where the sun is located; (ii) the bump at − 47 kilometers per second is due to a spiral arm feature about 8.3 kpc away; and (iii) the bump at − 73 km/sec is due to another feature about 10.4 kpc away. The fact that all three emission line peaks have corresponding absorption peaks in Fig. 5 means that Cyg X-3 is at least 10.4 kpc away. Three less solid arguments support the conclusion that Cyg X-3 is probably in the spiral arm feature about 10 kpc away. The first is that the absorption peak at − 73 km/sec is not as broad as might be expected, so perhaps not all the hydrogen in the feature is in the line of sight. The second is that in this direction a distance of 10 kpc places Cyg X-3 on the far edge of our galaxy, or else outside it. The third, complementary to the second, is based on the evidence that Cyg X-3 is not significantly outside our galaxy, hence it most probably is in the farthest feature in the spiral arm in that direction.

The hardest evidence that Cyg X-3 is not very distant comes from a measurement at very high resolution (*32*) made on 22–23 September, which showed that at that time the radio source was greater than 0.01 arc second in size. Because the radio source would not have begun expansion before about 18 September, the limitation of the speed of light places an upper limit of about 100 kpc on the distance to Cyg X-3. Perhaps equally powerful is the simple observation that, with a decay half-life of roughly 1 day largely due to adiabatic expansion losses, the radio source could not have been larger than 1 light day (10^{-3} pc) on, say, 4 or 21 September; with the speed of light as the limit for the expansion velocity, an upper limit of roughly 50 kpc can be placed on the distance.

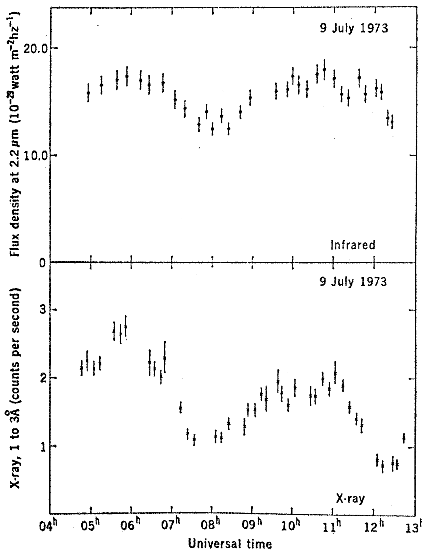


Fig. 6. The sinusoidal variations of Cyg X-3 in the infrared (wavelength, 2.2 μm $= 2.2 \times 10^{-6}$ cm) and x-ray (1 to 3 Å, 1 Å $= 10^{-8}$ cm) spectra on 9 July 1973, as measured by Becklin *et al.* (*34*).

The HI absorption measurements (*29*) also determine the hydrogen column density along the line of sight to be 1.7×10^{20} T_s atom cm^{-2}, where T_s is the excitation temperature for the hydrogen. This is compatible with the smallest densities inferred from the low energy x-ray cutoff if one can take T_s as approximately 150°K, a value which is only slightly larger than usual for the interstellar medium.

The general description of the Cyg X-3 events to be derived from the radio data involves a source at a distance of about 10 kpc, which expands as a bubble of relativistic particles and magnetic fields. A few days after the beginning the bubble is expanding at a few tenths the speed of light, attaining a size of the order of a light day in a few to several days, with magnetic fields of the order of several hundredths or a few tenths of a gauss at that time.

Cyg X-3 as an Optical and Infrared Source

The first optical observations of Cyg X-3 were at visual wavelengths and consisted of a few radio astronomers strolling outside their well-lit telescope control rooms to see if there was a new bright star in the sky at the right position, as might be possible if it had been a supernova event. The results were negative. Properly scientific optical studies were carried out at Mount Palomar by a Caltech group (*24*) using the 48-inch Schmidt camera and the 200-inch telescope. The group found no optical object on the position of the radio source down to a limit of 2.5×10^{-5} f.u. on 3 September and 2×10^{-6} f.u. on subsequent days (10^{-6} f.u. corresponds to a visual magnitude limit of 23.9). Considering the possible amounts of optical absorption, these results do not rule out the presence of even a relatively bright star at a distance of 10 kpc.

The first search for Cyg X-3 in the infrared was carried out on 3 October 1972 by a Caltech group (*33*) using the Hale 200-inch telescope and a very sensitive infrared photometer. An infrared source was discovered at wavelengths of 1.6 and 2.2 micrometers that was exactly coincident with the radio source. At this time the infrared source was not examined for variability or other unusual characteristics, and it was simply noted that the results were consistent with observations of a blue supergiant at a distance of 10 kpc if there were essentially complete absorption at visual wavelengths by the interstellar dust.

The most exciting contribution (*34*) of the infrared studies occurred during July 1973, when Cyg X-3 was found to be very variable in the infrared on many different time scales. First of all, when relatively weak in the infrared Cyg X-3 was found to vary sinusoidally with a period of 4.8 hours—exactly the same as for the x-ray source. This absolutely clinches the identification of the radio and infrared source with the x-ray source Cyg X-3. An example of the simultaneous x-ray and infrared sinusoidal variations of Cyg X-3 is shown in Fig. 6.

In addition to clinching the identification, the infrared result indicates that Cyg X-3 is the first object to show presumably binary or rotation phenomena in the infrared. Furthermore, the Cyg X-3 infrared source shows very active flaring on time scales as short as minutes. Such correlations promise to reveal a great deal about Cyg X-3. The possibilities are good that similar studies will reveal interesting relationships between the variations in x-rays and the infrared, and the usual variation of Cyg X-3 in the radio spectrum at the level of a few tenths of a flux unit, or less.

Cyg X-3 as Interpreted by Synchrotron Radiation Theory

Theoretical studies of synchrotron radiation sources have been extensively developed because of their application to well-observed objects like supernova remnants, quasars, and radio galaxies. The event of 2 to 13 September and the beginning of the event of 18 to 21 September in Cyg X-3 appear qualitatively as expected (*35*) for synchrotron radiation from an expanding bubble of relativistic particles and magnetic fields.

When cosmic ray particles are ejected from a very small region these relativistic particles begin an expansion which carries along magnetic fields that originally surrounded the system. The evolution of this expanding bubble of relativistic particles is then determined by: (i) the strength of the magnetic fields, (ii) the time variation of the particle ejection, (iii) the energy spectrum of the newly ejected particles, and (iv) the energy losses of the particles. The observable radiation is produced by synchrotron emission when cosmic ray electrons interact with the magnetic fields, but because of the compact nature of the initial Cyg X-3 source the major energy losses are due to adiabatic processes as the bubble increases its volume.

The Cyg X-3 radio events behave as if the initially ejected particles obey a power law in energy described by $E^{-\gamma}$, where γ is a constant. The initial increases observed on 2 September and 18–19 September show a source growing in size with considerable reabsorption of the emitted radio photons; because absorption processes are strongest at lower frequencies, a self-absorbed source is initially strongest at higher frequencies, and then becomes transparent in order of decreasing frequency (see Fig. 4).

Detailed analyses of the first Cyg X-3 radio outbursts have allowed the major parameters of the expanding radio sources to be determined. Many can be derived from the simplest of models (*35*), and more sophisticated models such as those discussed by Peterson (*36*) take into account more complex possibilities for the particle ejection and energy losses. One of the major conclusions that can be drawn from the radio data is that major particle ejection with γ approximately 2 lasted for 1 to 2 days for the event of 2 to 13 September, but three more successive episodes of particle ejection produced the three successive major peaks later in September. The major parameters for the radio events of Cyg X-3 are summarized in Table 1 where determinations are good to a factor of 3 or better.

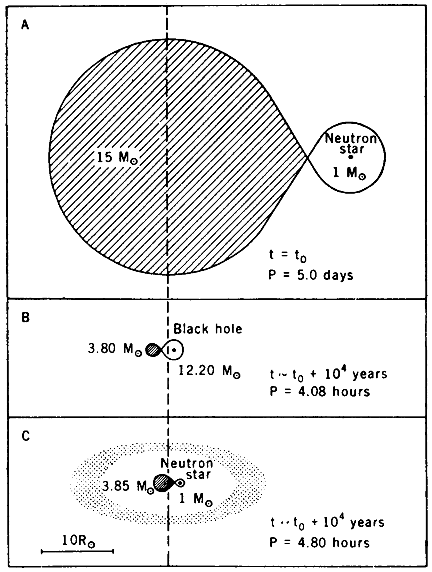


Fig. 7. Schematic representation of stages in a binary system that can evolve to produce very short period systems, as calculated by van den Heuvel and De Loore (*37*). Abbreviations are *t*, time; *P*, period. (A) Onset of the second stage of mass exchange. (B) Final system in the case of conservation of total mass and orbital angular momentum. (C) Final system in the case where mass is ejected from the binary—this state may represent Cyg X-3.

Table 1. Parameters for the radio events of Cyg X-3.

Parameter	Value
Distance	~ 10 kpc
Radio luminosity	$\sim 2 \times 10^{24}$ erg sec^{-1} hz^{-1}
Radio energy per event	$\sim 5 \times 10^{39}$ erg
Number of cosmic ray electrons per event	$\sim 10^{49}$
Energy in cosmic ray electrons per event	$\sim 5 \times 10^{44}$ erg
Velocity of expansion	$\sim 0.1 \times$ speed of light
Size ($t \sim 4$ days)	~ 1 light day $\sim 2 \times 10^{15}$ cm
Angular size ($t \sim 4$ days)	~ 0.02 arc second
Magnetic field ($t \sim 4$ days)	~ 0.1 gauss

Cyg X-3 as a Star System

The 4.8-day periodicity appearing in both the x-ray (*5, 7*) and infrared (*34*) emission of Cyg X-3 strongly suggests that the object is basically a double star system. From Kepler's law the knowledge of the period provides a relation between the separation of the two stars (a) and the sum of the masses (M_1 and M_2) such that (*35*)

$$a = 1.4[(M_1 + M_2)/M_\odot]^{1/3} R_\odot$$

where $M_\odot$ and $R_\odot$ indicate units of one solar mass and one solar radius, respectively. For any reasonable masses for the stars the separation cannot be more than one to a few solar radii, which is a very close binary system. In such systems the stars are usually in contact or nearly in contact with each other.

The question of how stars can evolve to this state has been discussed by van den Heuvel and De Loore (*37*). The process of evolution is as follows. In the beginning there are two normal stars in a binary system; the more massive of the two evolves with mass loss, attaining a stable final state as a neutron star. At this point a neutron star of 1 $M_\odot$ is in, say, a 5.0-day orbit with a 15-$M_\odot$ star, which then evolves until it fills the critical gravitational equipotential surface that is usually called a Roche lobe. This is shown in Fig. 7A. There are then two extreme possibilities, depending on whether the subsequent mass loss from the 15-$M_\odot$ star is transferred to the neutron star or escapes from both stars. In the first case (Fig. 7B) the star losing mass attains a stable state at 3.8 $M_\odot$, while the addition of more mass forces the neutron star to continue collapse into a black hole. With the other option the lost mass escapes from the system, leaving a 3.85-$M_\odot$ stable star and an unchanged neutron star (Fig. 7C). In the first case the final orbit has the stars separated by 3.5 $R_\odot$, while the second case leaves the stars separated by 2.4 $R_\odot$. The option resulting in a neutron star is probably closest to being applicable to Cyg X-3 because of the probable importance of mass transferring to the compact object, though the truth may be somewhere in between.

All the evidence suggests that Cyg X-3 as an x-ray and infrared source is produced by an extensive hot plasma surrounding a much more compact object. Presumably the x-ray and infrared source is eclipsed by the companion star once every 4.8 hours. In this context the radio emission probably results from interesting transient events in the unstable outer parts of the x-ray and infrared emission regions.

Cyg X-3 as a Cosmic Ray Accelerator

The clear interpretation of the Cyg X-3 radio events of September 1972 in terms of synchrotron radiation means that the penultimate cause of the radio events is processes of acceleration and ejection of cosmic ray electrons from the central system. In the context of what is known about the x-ray, infrared, and radio source this suggests that the basic acceleration mechanisms operate in the unstable outer portions of the very hot plasma filling the Roche lobe around the compact star. It is not clear whether the basic processes are similar to the flare events known to accelerate particles on the sun or to a relativistic and variable stellar wind analogous to the well-known solar wind (which has a lower velocity). The essentially continuously variable nature of the weak radio emission from Cyg X-3 shows that such processes are operating continuously.

The outbursts of Cyg X-3 in September 1972 are unusual, even for Cyg X-3; therefore one must ask for the ultimate cause of the modification of "normal" behavior which produced such unusual events. Since the ejection of such large numbers of relativistic particles must be transient, one must seek some sort of transition from one moderately stable state to another, with the large outburst being a result of the transition itself. The most likely possibility is a transient change in structure in one or the other of the two stars—a "starquake." Such starquakes presumably are transient alterations on the natural dynamical time scale of the star: $t_{\mathrm{dyn}} \sim (R^3/GM)^{1/2}$, where R and M are the radius and mass of the star, and G is the gravitational constant. For $M \sim 1\,M_\odot$ and $R \sim 1R_\odot$, $t_{\mathrm{dyn}} \sim 27$ minutes. Successive events could be associated with "aftershocks" of such alterations of structure. In the case of a change in the mass ejection of the normal star, the result could be a temporary increase in mass infall for the other star with its sensitive hot plasma "atmosphere." On the other hand, a change in structure (continued gravitational collapse?) in the compact object could also have drastic effects on its atmosphere and on the processes that continually produce the radio emission.

Cyg X-3, a New Phenomenon in the Sky

The object known as Cyg X-3 is in the process of altering many of our preconceptions. For the radio astronomer there is now the realization that the radio sky could be filled with interesting, transient radio sources blinking on and off—and without a fantastic stroke of luck or serendipity we would never know about most of them. For the infrared astronomer there is the surprising correlation with x-ray and radio astronomy found in the first infrared object showing probable binary characteristics. For the x-ray astronomer there is the puzzle of the shortest period x-ray binary known (by a factor of 10), which is only the second known x-ray source showing coupling between x-ray and radio events. Finally, for those interested in cosmic rays and their acceleration mechanisms, Cyg X-3 requires that such phenomena be produced in a stellar system with interesting x-ray and infrared emission. All of this certainly makes Cyg X-3 one of the most interesting of astronomical puzzles.

References and Notes

1. R. Giacconi, P. Gorenstein, H. Gursky, J. R. Waters, *Astrophys. J. Lett.* **148**, 119 (1967).
2. H. Gursky, P. Gorenstein, R. Giacconi, *ibid.* **150**, 75 (1967); P. Gorenstein, R. Giacconi, H. Gursky, *ibid.*, p. 85.
3. R. Giacconi, *Non-Solar X- and Gamma-Ray Astronomy*, L. Gratton, Ed. (Reidel, Dordrecht, Netherlands, 1970), p. 107.
4. R. D. Bleach, E. A. Boldt, S. S. Holt, D. A. Schwartz, P. J. Serlemitsos, *Astrophys. J.* **171**, 51 (1972).
5. D. R. Parsignault, H. Gursky, E. M. Kellogg, T. Matilsky, S. Murray, E. Shreier, T. Tananbaum, R. Giacconi, *Nature Phys. Sci.* **239**, 123 (1972).
6. S. Murray, H. Gursky, C. Jones, E. Shreier, H. Tananbaum, R. Leach, D. R. Parsignault, abstract of paper to be presented at the 141st meeting of the American Astronomical Society, Tucson, Arizona (December 1973).
7. P. W. Sandford and F. H. Hawkins, *Nature Phys. Sci.* **239**, 135 (1972).
8. J. G. Ables, *Astrophys. J. Lett.* **155**, 27 (1969); R. M. Hjellming and C. M. Wade, *ibid.* **164**, 1 (1971); C. M. Wade and R. M. Hjellming, *Astrophys. J.* **170**, 523 (1971).
9. R. M. Hjellming and C. M. Wade, *Astrophys. J. Lett.* **168**, 21 (1971).
10. L. L. E. Braes and G. K. Miley, *Nature* **232**, 246 (1971); C. M. Wade and R. M. Hjellming, *ibid.* **235**, 271 (1972).
11. R. M. Hjellming and L. Blankenship, *Nature Phys. Sci.* **243**, 81 (1973).
12. L. L. E. Braes and G. K. Miley, *Nature* **237**, 506 (1973).
13. R. M. Hjellming, M. Hermann, E. Webster, *ibid.*, p. 507.
14. R. M. Hjellming and B. Balick, *ibid.* **239**, 443 (1972).
15. R. M. Hjellming, *X- and Gamma-Ray Astronomy*, H. Bradt and R. Giacconi, Eds. (Reidel, Dordrecht, Netherlands, 1973), p. 98.
16. A. Brisken, thesis, University of Maryland (1973).
17. P. C. Gregory, P. P. Kronberg, E. R. Seaquist, V. A. Hughes, A. Woodsworth, M. R. Viner, D. Retallack, *Nature* **239**, 440 (1972).
18. H. D. Aller and W. A. Dent, *Nature Phys. Sci.* **239**, 121 (1972).
19. D. B. Shaffer, G. A. Shields, B. Schupler, *ibid.*, p. 131.
20. W. A. Dent, J. E. Kapitzky, B. G. Leslie, G. Kojoian, M. L. Meeks, H. H. Danforth, J. J. Kollasch, E. J. Chaisson, D. F. Dickinson, L. E. Goad, C. J. Lada, *ibid.*, p. 126.
21. W. A. Dent, *ibid.*, p. 127.
22. A. H. Bridle, M. J. L. Kesteven, A. E. Niell, *ibid.*, p. 121.
23. R. B. Pomphrey and E. E. Epstein, *ibid.*, p. 125.
24. J. A. Westphal, J. Kristian, J. P. Huchra, S. A. Shectman, R. J. Brucato, *ibid.*, p. 134.
25. J. P. Conner, W. D. Evans, D. E. Mook, *ibid.*, p. 125.
26. R. M. Hjellming and B. Balick, *ibid.*, p. 135.
27. L. L. E. Braes, G. K. Miley, W. W. Shane, J. W. M. Baars, W. M. Goss, *ibid.* **242**, 66 (1973).
28. R. Lauqué, J. Lequeux, Nguyen-Quang-Rieu, *ibid.* **239**, 119 (1972).
29. K. W. Chu and J. H. Bieging, *Astrophys. J. Lett.* **179**, 22 (1973).
30. B. Anderson, R. G. Conway, R. J. Davis, R. J. Peckman, P. J. Richards, R. E. Spencer, P. N. Wilkinson, *Nature Phys. Sci.* **239**, 117 (1972).
31. F. N. Bash and F. D. Ghigo, *ibid.* **241**, 93 (1973).
32. H. F. Hinteregger, G. W. Catuna, C. C. Counselmann, III, R. A. Ergas, R. W. King, C. A. Knight, D. S. Robertson, A. E. E. Rogers, I. I. Shapiro, A. R. Whitney, T. A. Clark, L. K. Hutton, G. E. Marandino, R. A. Perley, G. Resch, N. R. Vandenberg, *ibid.* **240**, 159 (1972).
33. E. E. Becklin, J. Kristian, G. Neugebauer, C. G. Wynn-Williams, *ibid.* **239**, 130 (1972).
34. E. E. Becklin, G. Neugebauer, F. J. Hawkins, K. D. Mason, P. W. Sanford, K. Matthews, C. G. Wynn-Williams, *Nature* **245**, 302 (1973).
35. P. C. Gregory, P. P. Kronberg, E. R. Seaquist, V. A. Hughes, A. Woodsworth, M. R. Viner, D. Retallack, R. M. Hjellming, B. Balick, *Nature Phys. Sci.* **239**, 114 (1972).
36. F. W. Peterson, *Nature* **242**, 173 (1973).
37. E. P. J. van den Heuvel and C. De Loore, *Astron. Astrophys.* **25**, 387 (1973).

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