CYGNUS X-3: IS THERE CONVINCING EVIDENCE FOR NEW PHYSICS?

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Cygnus X-3 is a highly interesting source, certainly astrophysically and possibly from the point of view of particle physics as well. It is an intense and variable x-ray, infrared, radio, and γ-ray source initially observed by Giacconi et al[1] in 1966 and generally interpreted as an x-ray binary with a 4.79 hr orbital period[2-4]. Evidence has been reported for 10^{15}-10^{16}eV air showers coming from the direction of Cygnus X-3 with the characteristic 4.8 hr period[5,6] and for surprisingly intense fluxes of high energy underground muons[7,8]. The x-ray, radio, and γ-ray observations are briefly reviewed here, with emphasis on the time variability, and the underground muon results are described critically and in detail. It is concluded that at present, based primarily on the unconvincing statistics and lack of confirmation, there is still insufficient firm evidence for underground muon fluxes from Cygnus X-3 and for the new particle physics which would be required by confirmation of the reported Soudan and NUSEX underground muon results.

I. X-Ray Results. The properties of Cygnus X-3 (and in particular the detailed x-ray and radio results) have been described fully elsewhere[2-4]. These results will only be summarized here. The raw 1.5-15 keV x-ray counting rate recently seen by the EXOSAT satellite[9] is shown in Fig. 1. A strong 4.79 hr modulation is clearly seen in the data. Folding the data using the ephemeris of van der Klis and Bonnet-Bidaud[10] gives the slightly asymmetric x-ray light curve of Fig. 2, with a relative modulation of 47%. The period is very stable[11] ($\dot{P}$ = 7.8 x 10^{-10}), suggesting that it is an (unusually short) orbital period. On the assumption that the system consists of a neutron star and a normal companion filling its Roche lobe, Kepler's Law yields a binary separation no greater than $2R_{\odot}$. Based on mass-radius relationships for normal hydrogen and helium stars, the companion mass must be between 0.5 and 4 $M_{\odot}$[12]. The x-ray luminosity of between 10^{37} and 10^{38} ergs sec^{-1} (assuming a distance of 11 kpc[13]) is close to the Eddington limit and makes

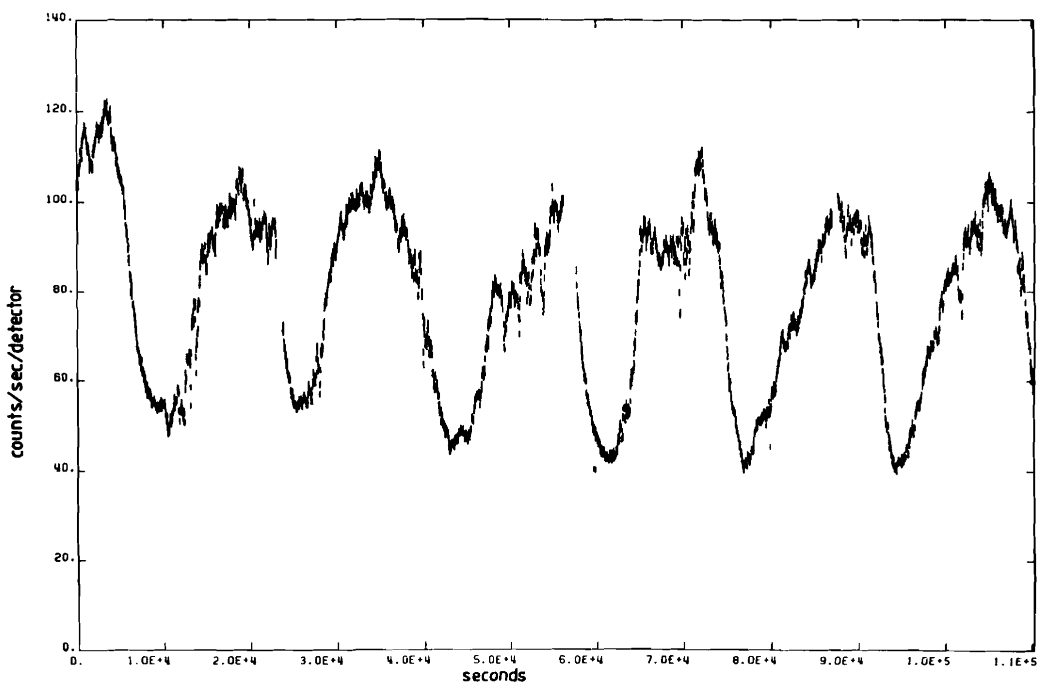


Fig. 1. Raw 1.5 - 15 keV counting rate observed by the EXOSAT satellite from Cygnus X-3 (from ref. 9).

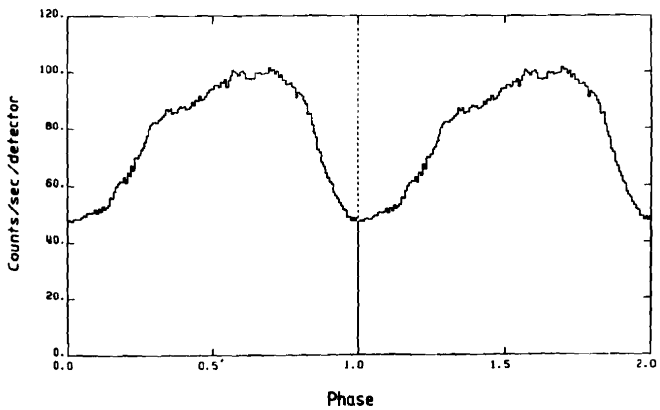


Fig. 2. EXOSAT x-ray light curve[9].

Cygnus X-3 one of the brightest sources in the galaxy.

It should be noted, however, that the light curve does not go completely to zero, as would a true eclipse. By contrast, the x-ray light curves for three similar sources (X 1916-053, X 1822-371, and EXO 0748-676, with periods 50 min, 5.75 hrs, and 7 hrs respectively) show the same broad modulation as in Cygnus X-3, but in addition the sharp modulation to zero due to a true eclipse by a companion[11,14] (Fig. 3). Although the modulation of the Cygnus X-3 light curve has often been discussed in terms of scattering and absorption in a stellar wind or surrounding shell[9,15], the comparison to the x-ray light curve of Fig. 3 suggests an accretion disk corona model similar to that developed in some detail[14] for X 1822-371, in which the x-rays are generated at the neutron star but scattered and modulated by an extensive ionized corona formed from an accretion disk by the radiation pressure of the neutron star emitting near the Eddington limit. The scattering corona would produce an apparent x-ray source of fairly large spatial extent, and would also serve to obscure the time structure of x-ray emission from a rapidly spinning central pulsar (although it would not obscure the pulsar's γ-ray time structure -- cf. Sec. V).

The modulation seen by EXOSAT decreases from 47% in the 1.5-15 keV band to 25% over the range 10-30 keV. Similar behavior is seen in the OSO-7 x-ray light curves of Fig. 4, where the modulation can clearly be seen to decrease with increasing x-ray energy[16]. The spectra in Fig. 5 characteristically show a blackbody behavior with added absorption at low energies, together with a power law tail at higher energies. In the case of the EXOSAT spectra in Fig. 5a, the column density of hydrogen required to produce the needed absorption is 6 - 8 x 10^{22} cm^{-2}; for the earlier rocket data of Fig. 5b, $n_H \sim 2.6 - 2.7 \times 10^{22}$ cm^{-2}. If interstellar absorption[13] accounts for 1.4 x 10^{22} cm^{-2}, the remaining 1 - 7 x 10^{22} cm^{-2} is presumably due to a time-varying local absorbing medium.

When the 4.8 hr periodicity is filtered out of the raw EXOSAT counting rate, the remaining short-term variability is shown in Fig. 6. Large variations within a single 40 sec bin indicate the presence of inhomogeneities

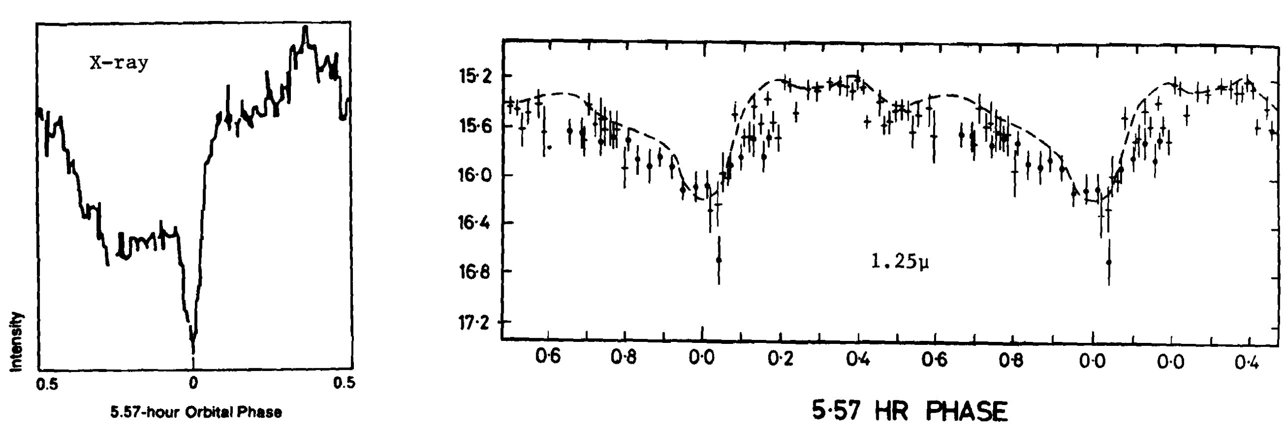


Fig. 3. X-ray light curve of the x-ray binary X1822-371 (left, from Cordova, ref. 14) and the 1.25μ infrared light curve (right, from Mason and Cordova, ref. 14), showing a sharp eclipse superimposed on a modulation due to scattering from an accretion disk corona.

within the source with dimensions $\lesssim 10^{12}$ cm. The rms scatter in the residual counting rate reaches a maximum near phase 0.2, at a level of approximately 17% of the mean intensity at that phase.

Over longer time intervals, the COS B, Ariel 5, and Vela 5B x-ray results also indicate a high degree of variability, as shown in Fig. 7, where variations in excess of a factor of 10 in the overall intensity occur on time scales of weeks to months[17].

II. Medium-Energy γ-Rays. The power law in Fig. 5 has been seen[18] at energies up to about 400 keV, although the differential spectral index has appeared to vary between 2.2 and 3.6. A gap in the observations exists from hard x-ray energies up to medium energy gamma rays. In March of 1973, however, the SAS 2 satellite reported[19] a 4.5σ excess of γ-rays above 35 MeV. The SAS-2 light curve (Fig. 8) shows the same asymmetric shape as the x-ray curve, with a peak close to the x-ray peak near phase 0.7, but the γ-ray curve falls completely to background at x-ray minimum. Galper et al[20], observing with a balloon-

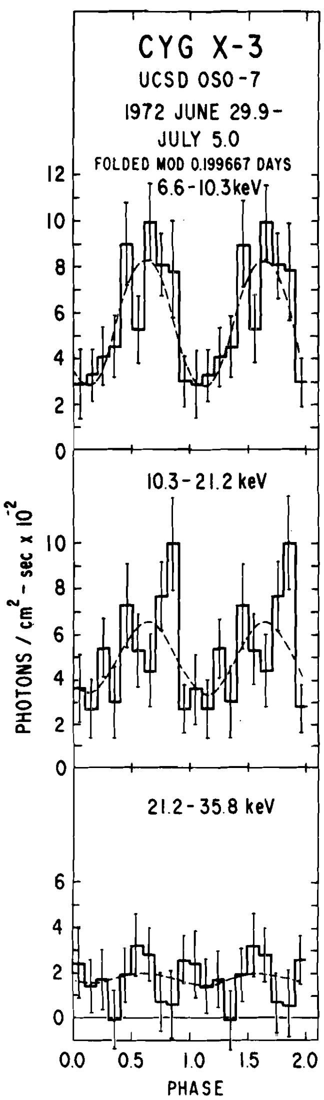


Fig. 4. OSO-7 x-ray light curves[16]

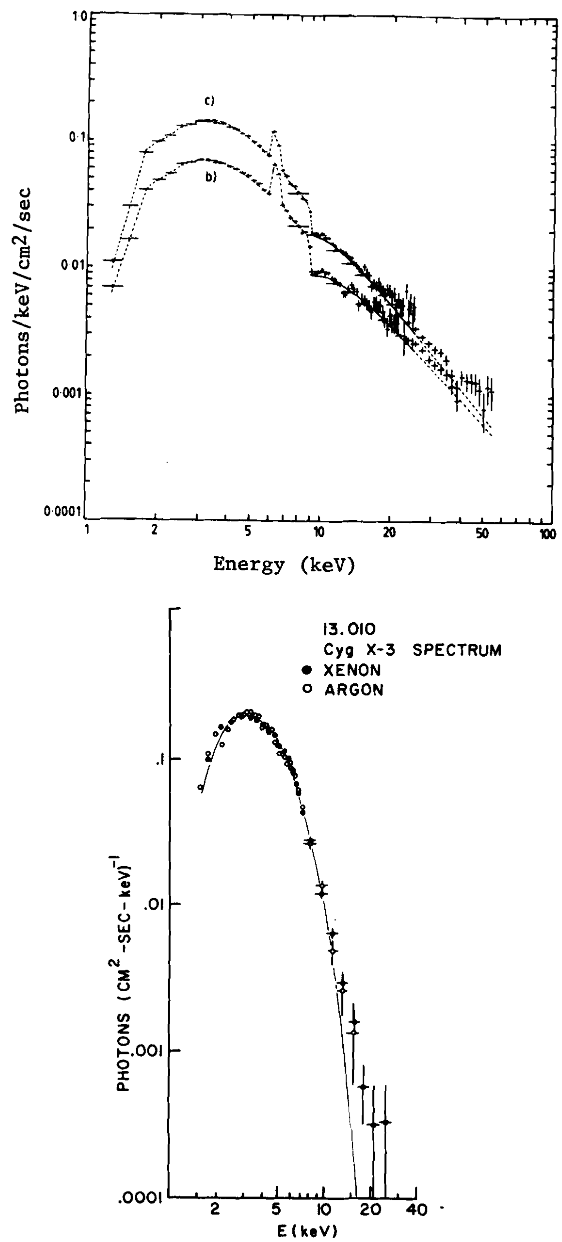


Fig. 5. Spectrum measured by EXOSAT in 1983 (upper figure) and in 1973 rocket flight (ref. 55, lower figure).

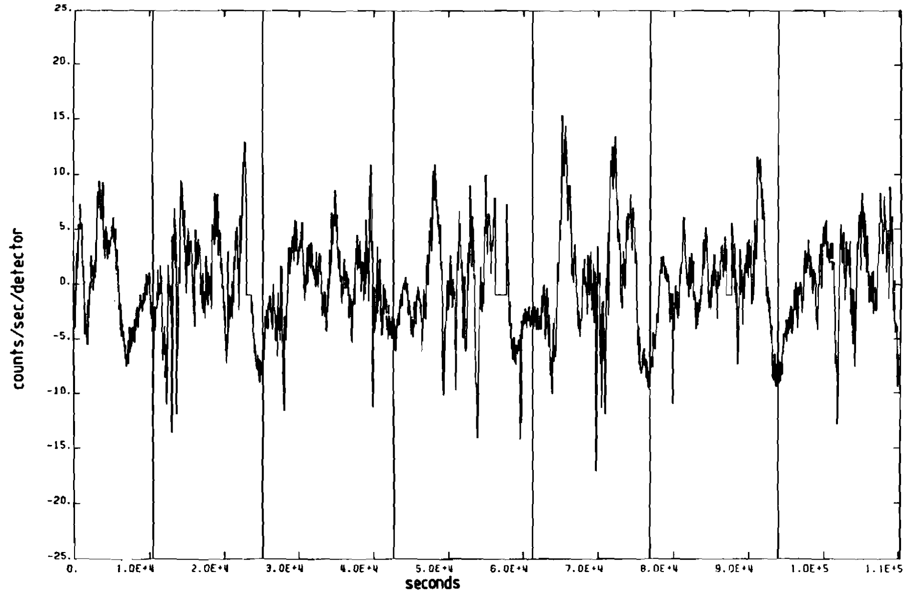


Fig. 6. Fast time variability measured by EXOSAT (ref. 9). Bin size is 40 sec.

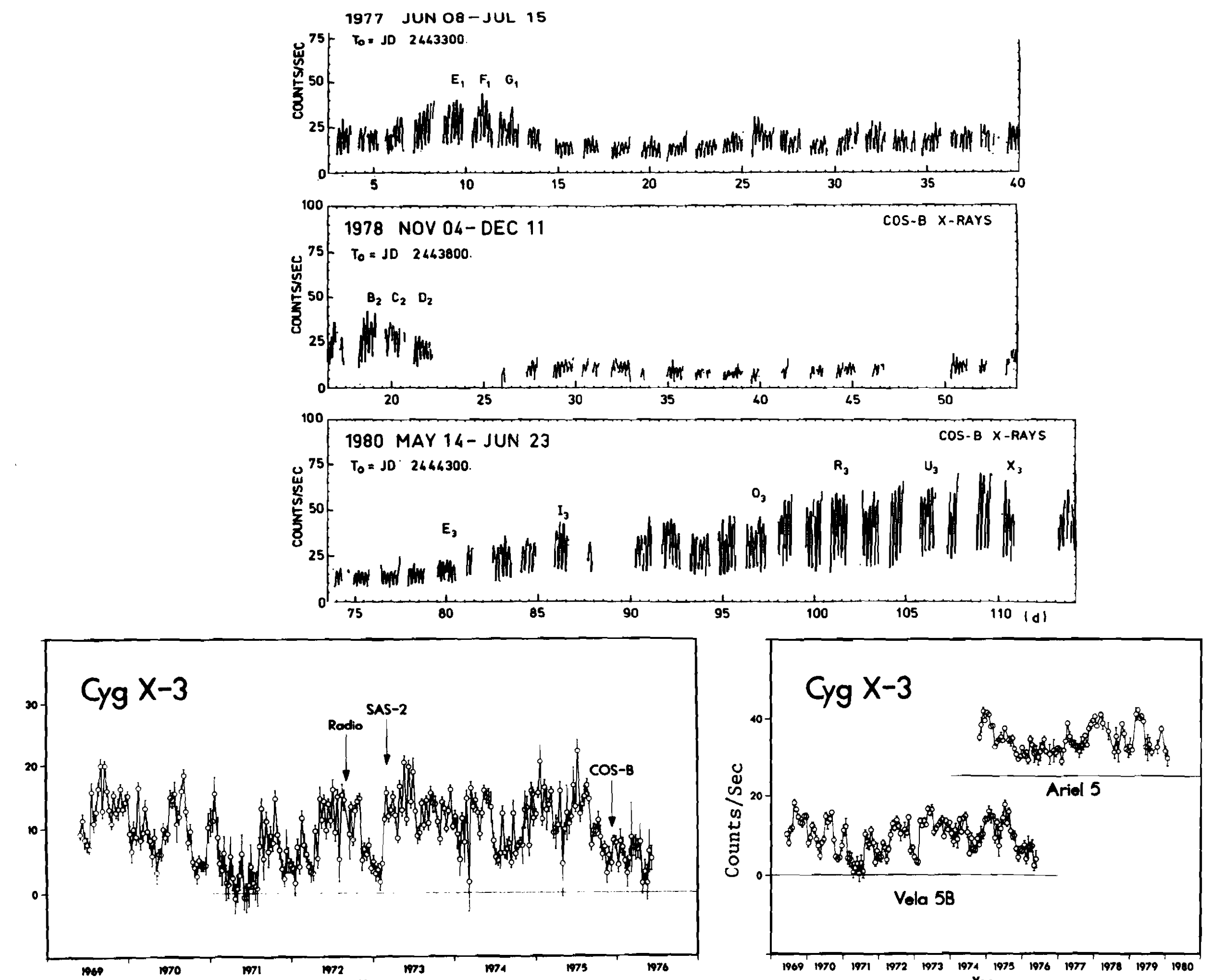


Fig. 7. Upper figure: Long term x-ray variability measured with the COS-B x-ray detector (ref. 56). Lower left: 10-day average x-ray counting rates seen with Vela 5B. Positions of the 1972 radio flare, and the SAS-2 and initial COS-B observations are shown (ref. 17). Lower right: 20-day averages of Vela 5B and Ariel 5 measurements. The Ariel 5 data are scaled upward by a factor of 40.

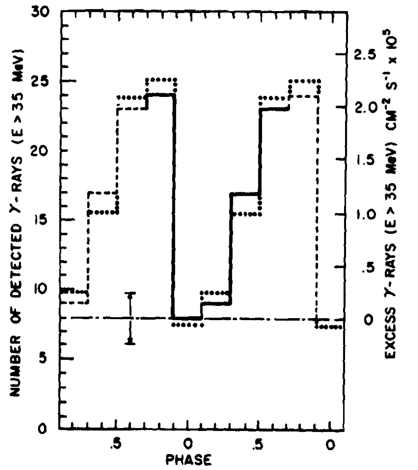


Fig. 8. SAS-2 γ-ray (> 35 MeV) light curve.

borne detector during the intense radio flare in October, 1972, reported a 3.6σ enhancement in the γ-ray counting rate during the phase interval 0-0.2, but saw nothing during a flight in 1974. Other balloon experiments have seen no excess signal[21] (although the durations of these observations were all shorter than 4.8 hrs), and the COS-B satellite[22], with similar sensitivity but better angular resolution than SAS-2, also reports no excess flux with the characteristic 4.8 hr period from Cygnus X-3. In fact, based on seven observations between 1975 and 1982, the COS-B group have set 2σ upper limits an order of magnitude below the SAS-2 flux level. It is perhaps worthwhile to note that the positive γ-ray measurements were made at times of high x-ray intensity, while at least the initial negative COS-B result came from a time of lower overall x-ray intensity (Fig. 7).

III. Radio Observations. If the non-thermal spectrum of Fig. 5 extends up to 100 MeV with a spectrum $dN/dE \sim E^{-2}$, then the γ-rays passing through the surrounding thermal medium will produce energetic electrons by inverse Compton scattering of ambient electrons and electron-positron pair production. In the presence of a magnetic field, the electrons will radiate by synchrotron emission[23]. The expected quiescent radio level of 10^{31} erg sec^{-1} has been observed[24].

In particular, Hjellming and Balick[25] measured a flux of 0.01 - 0.04 f.u. (1 f.u. = 10^{-26} W $m^{-2}Hz^{-1}$) at 8085 MHz on Aug. 31, 1972; in an observation on Sept. 2, however, Gregory et al.[25] observed an unexpectedly high flux of 21 f.u. at 10522 MHz. The time history of the subsequent observations is shown in Fig. 9, where it is seen that major flaring activity lasted from the beginning of September until late October, with the initial burst reaching a level some 10^3 times higher than the quiescent level. The source was initially optically thick, reaching a maximum earlier at high frequencies than at low frequencies (Fig. 9) and then decaying on time scales of days. The observed flaring matched the behavior of an expanding cloud of energetic electrons

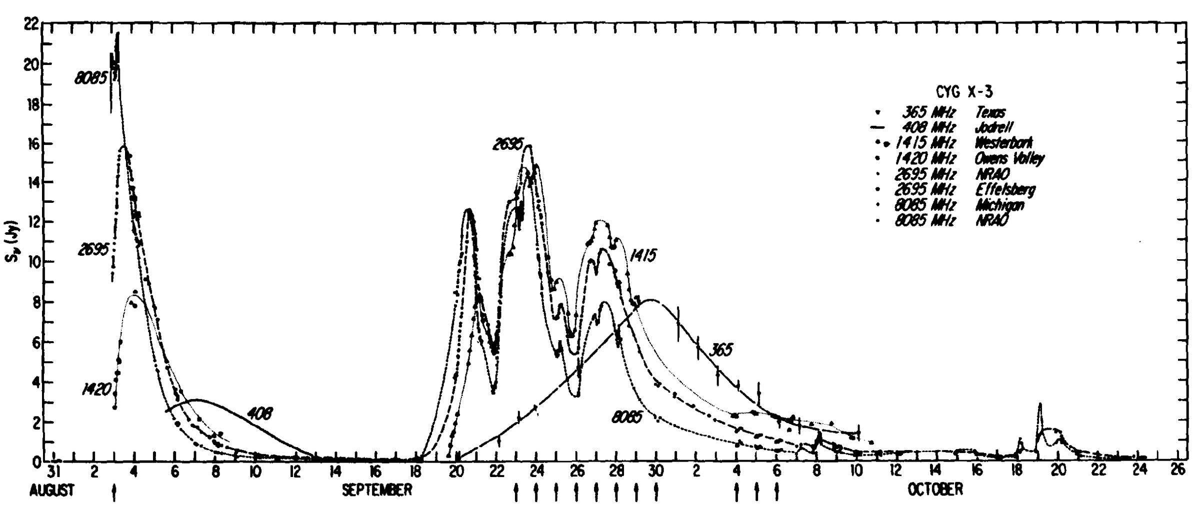


Fig. 9. Radio flux densities measured at eight frequencies during the giant 1972 flares.

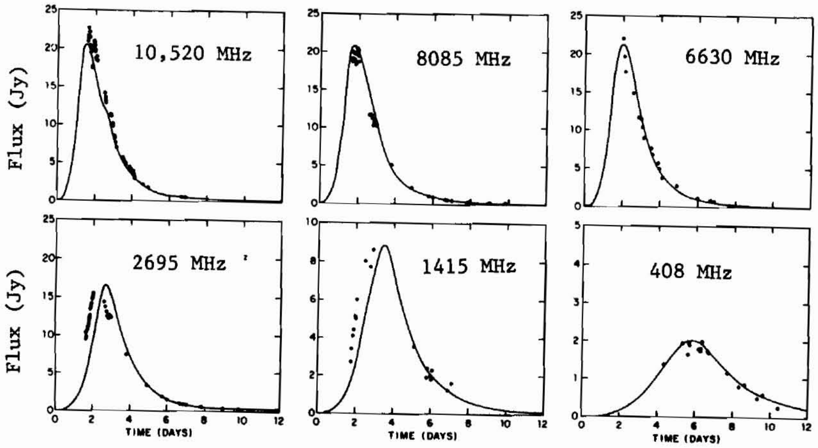


Fig. 10. Calculated flux compared to observations for the initial September 1972 radio flare (from Marscher and Brown, ref. 26).

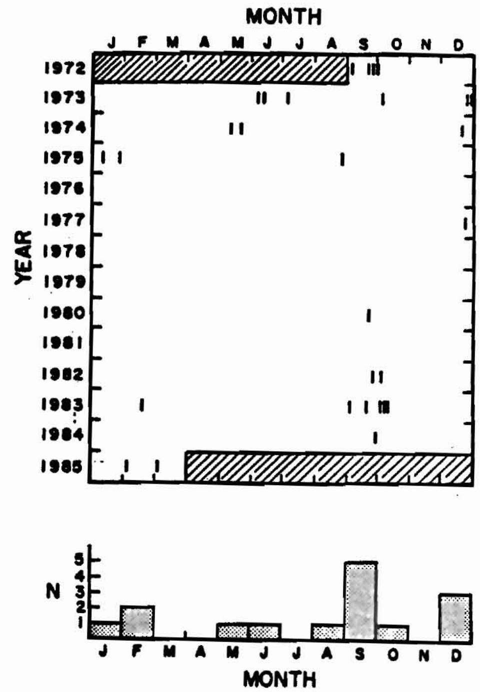


Fig. 12. History of large Cyg X-3 radio flares vs. time (ref. 28).

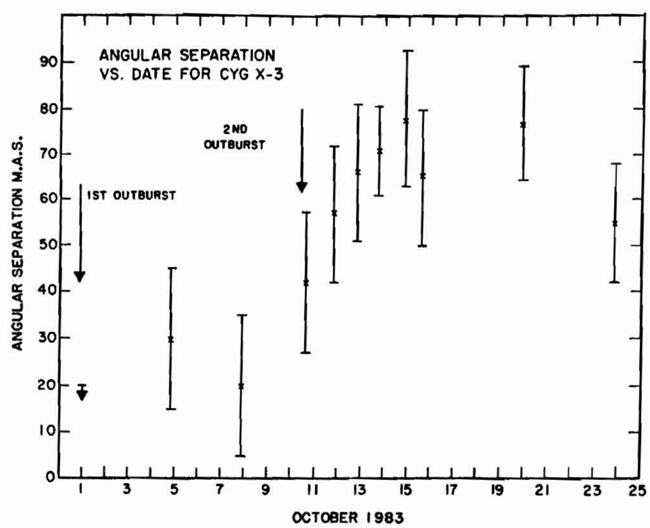


Fig. 11. Measured angular separation vs. time for the October 1983 radio outburst.

radiating synchrotron emission in the presence of a magnetic field, taking into account the effects of synchrotron self-absorption and free-free absorption in the ambient medium[26] (Fig. 10). In subsequent flares in 1982 and 1983, Geldzahler et al.[27] and Spencer et al.[27] measured expansion velocities v $\sim$ 0.4c directly using the VLA and MERLIN interferometers (Fig. 11).

Although the 1972 flare was an unprecedented and spectacular event, such flares now appear to occur repeatedly and reasonably predictably[28]. With the notable exception of the October 1985 event[29], these flares all have the same expanding synchrotron behavior as was first observed in 1972. Fig. 12 shows a plot of the times of occurrence of major radio flares from Cygnus X-3. The observations were sporadic during 1976-1981; during times of good coverage, however, it appears that a large flare always occurs during September-October. The figure was drawn in March, 1985; since then, two more large flares occurred in October and December, 1985. Johnston[29] predicts the most likely time of occurrence for the next large event to be mid-October, 1986.

The 4.8 hr x-ray period is not observed in the large radio flares, but Grindlay and Molnar[2,4] have recently reported evidence for a 4.95 hr period during intervals of relatively quiet emission. They interpret these results in terms of models involving either a periodic modulation of the binary orbit or a third body in the Cygnus X-3 system which perturbs the orbits of the neutron star and companion. As described by Grindlay in these proceedings[2], they observe constant small electron synchrotron flares, and suggest that the giant flares may be due to cataclysmic mass transfer events at periastron.

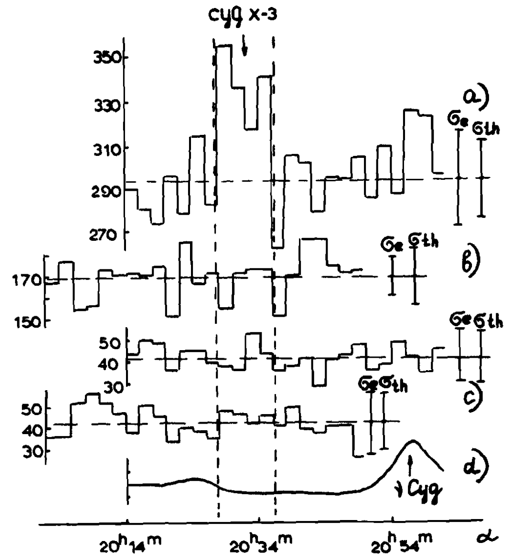
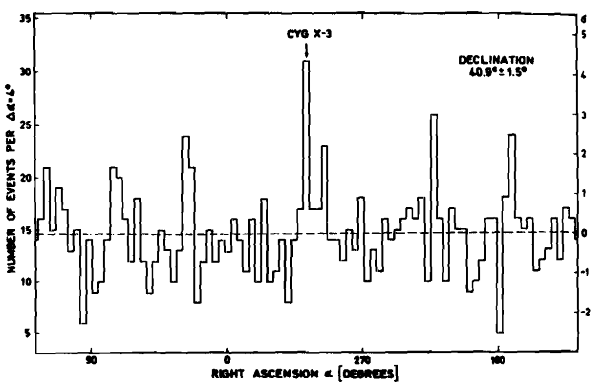
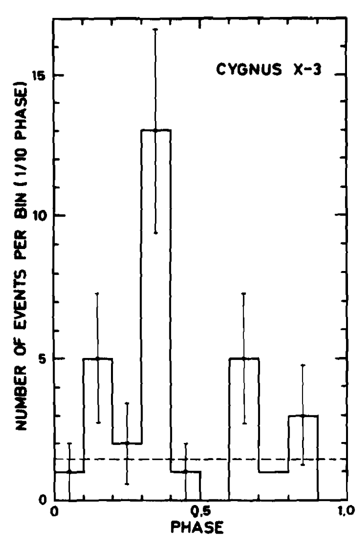


Fig. 13. Intensity (counts/2 min) vs. right ascension measured by Vladimirsky et al (ref. 32) on Sept. 8-9, 1972. Curve a: above 1 TeV; b: above 1.8 TeV; c: random counting rates for the two energy ranges; d: background brightness of the night sky.





IV. Infrared and Optical Emission. Since Cygnus X-3 lies in a crowded and dusty region of the sky close to the galactic plane, its optical emission is obscured. Westphal[30] suggests a limit on the apparent visual magnitude of 23.9. Non-steady thermal infrared emission has been detected[31] with the 4.8 hr orbital period and recurrent flaring behavior which is apparently uncorrelated with the x-ray variability.

V. High-Energy Gamma Rays. In the very high energy gamma ray regime, Vladimirsky et al.[32] pointed two 1.5 m diameter Cerenkov mirrors at Cygnus X-3 during the period 9/5/72 - 11/1/72 (i.e., spanning the time of the intense 1972 radio flares). In one mirror, operating at a threshold of 10^{12} eV, they observed a 5σ excess as the source drifted across the field of view at phases 0.3 and 0.9 on the nights of Sept. 8-9; with the second mirror, operating at energies above 1.8×10^{12} eV, no enhancement was observed. Their counting rates are shown in Fig. 13 plotted against time. With six years of accumulated observations, the same group reports a 5.4σ peak at a phase of 0.2 and a 3σ excess near phase 0.8.

Samorski and Stamm[5], using the Kiel air shower array, have observed an excess of 2×10^{15} - 2×10^{16} eV air showers arriving from the direction of Cygnus X-3. When they fold their data using the (somewhat old) ephemeris of Parsignault et al.[33], they find a peak in the phase plot at $\varphi = 0.3 - 0.4$ (Fig. 14). Although their phase plot has been criticized on the grounds that they have used an older ephemeris, this in no way reflects on their raw counting rate excess from the Cygnus X-3 direction. The Haverah Park group[6] have seen a similar signal, with an indication for a cutoff above 2×10^{16} eV.

A summary of the experiments above 5×10^{11} eV which have reported positive signals from

Fig. 14. Upper curve: Number of large ($N_e \gtrsim 10^5$) air showers seen by Kiel with age parameter $s \gtrsim 1.1$ in a 3^0 declination band around Cygnus X-3. Lower curve: Phase plot from 3^0 window in declination and 4^0 window in r.a. around Cyg. X-3.

Cygnus X-3 is given in Fig. 15. Although several of the observations are at only marginal levels of significance, and although there have been a much larger number of negative results, there are sufficiently many positive observations that it appears certain that the source has intervals of high intensity when it can be (and has been) clearly detected interspersed with low intensity intervals. As in the x-ray, the time scales for these amplitude (and possibly phase) variations are at most months. For example, in Oct-Nov 1983, Cawley et al.[34] observed a 4.4σ signal with the 10m imaging reflector at Mt. Hopkins; a month later under similar conditions the same group saw nothing. Especially noteworthy among these high energy results is the Dugway Cerenkov observation[35] of a 12.5908 $\pm$ 0.0003 msec pulsar emitting gamma rays above 10^{12} eV.

Watson[36] has shown a set of representative phase plots from several of these high-energy experiments (Fig. 16), and has plotted the phases during the 4.8 hr period at which different observers find enhancements (Fig. 17). At the highest energies, above 10^{15} eV, Akeno and Haverah Park report excesses near 0.6 - 0.7, and Kiel, Fly's Eye, and Haverah see peaks near 0.25; between 10^{13} and 10^{15} eV there are a clumping of observations near phase 0.5 - 0.7, with nothing in the lower phase region; and near 10^{12} eV there are several measurements at phases 0.6 - 0.7 as well as the Dugway, Whipple, and Crimean results at phases between 0.15 and 0.3. Although there appear to be two distinct regions of the phase diagram (0.15 - 0.3 and 0.5 - 0.7) where the observations are clumped, there is clearly no well-defined "right" phase. Rather, the phase of maximum emission seems to bounce around either as a function of time or energy.

The observed intensities shown in Fig. 15 suggest that (when the source is in an "on" state) the emission follows a flat differential E^{-2} spectrum from 10^{12} up to about 10^{16} eV. There is no good evidence to support the contention of Bhat et al.[37] that the high energy flux is suffering a long-term exponential decrease with an e-folding time of 1.7

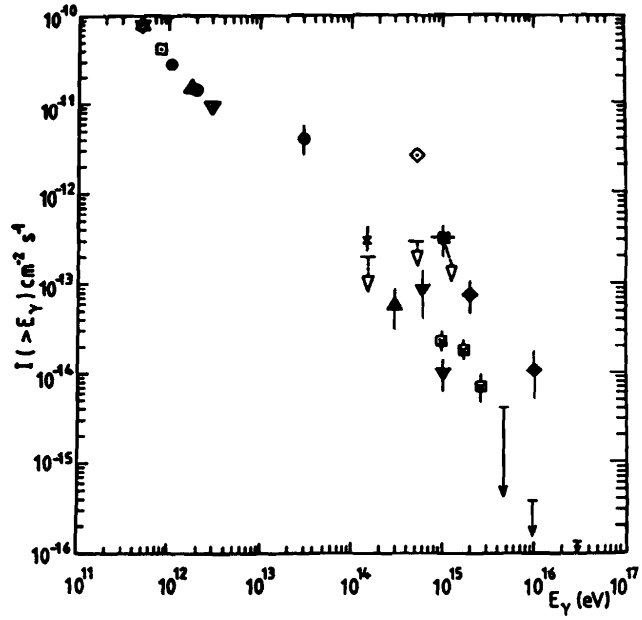


Fig. 15. Measured intensities above 5 x 10^{11} eV from Cygnus X-3 (adapted from ref. 36). Sources are given in ref. 57.

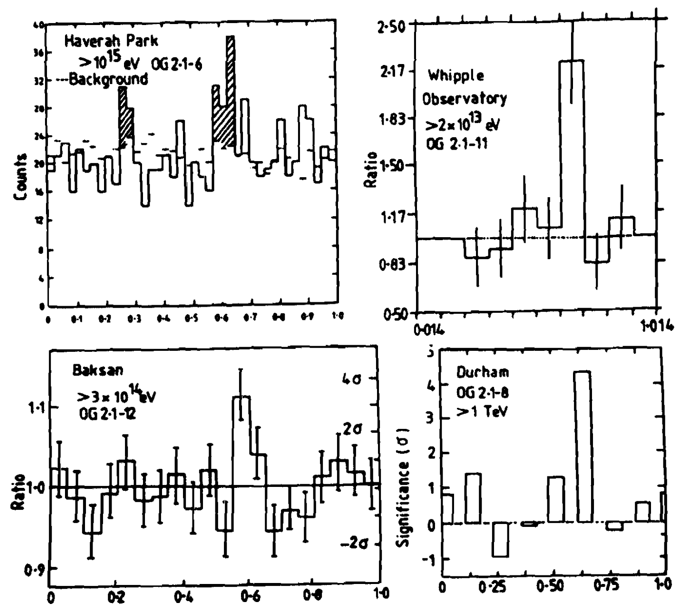


Fig. 16. Phase plots from selected high energy observations: Haverah Park, ref. 6; Whipple, ref. 57 (Cawley et al.); Baksan, ref. 54; Durham, ref. 57 (Chadwick et al.).

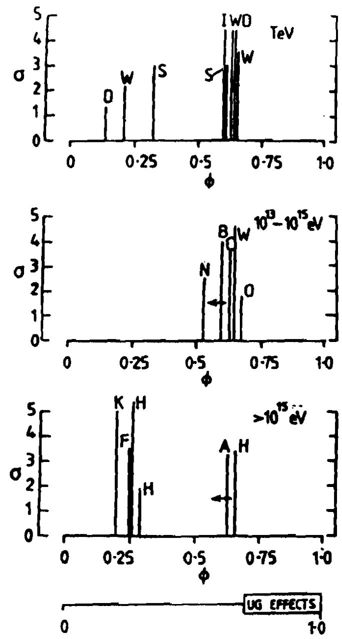


Fig. 17. Phases of peak emission seen by various observers from Cygnus X-3.

years. Rather, above 3 x 10^{15} eV the Haverah Park group[6] measured an integral intensity of (1.5 ± 0.3) x 10^{-14} $cm^{-2}sec^{-1}$ between 1979 and 1982; and in 1984 they measure 4.5 - 7 x 10^{-14} cm^{-2} sec^{-1}. Taking into account the attenuation due to γ-γ pair production on the 3° background ($\lambda \sim 7$ kpc) and assuming isotropic emission from a source 10 kpc away, Lloyd-Evans et al.[6] suggest a source luminosity in γ-rays above 3 x 10^{15} eV of 3 x 10^{36} erg sec^{-1}. Hillas [38] calculates the power in primary 10^{17} eV protons at the source to be 3 x 10^{39} erg sec^{-1}. By contrast, the total cosmic ray emission of the galaxy above 3 x 10^{15} eV is only 8 - 20 x 10^{38} erg sec^{-1}; so that there is room for very few sources like Cygnus X-3 in the entire galaxy.

Gamma rays at TeV energies may well be the result of electron synchrotron losses and curvature radiation in an intense magnetic field. At 10^{15} eV energies, however, electrons lose energy too rapidly to be accelerated. For the case of a 10^8 G field[39], the lifetime of a 10^{15} eV electron is 10^{-18} sec; even in a 1 G field, the electron survives only 25 msec. Instead, accelerated protons presumably collide with intervening gas and dust to produce charged and neutral pions, which then decay into energetic gamma rays and neutrinos. In the case of the x-rays, the absorbing medium has a column thickness ~ 0.1 g cm^{-2}; since a proton interaction length is closer to 10^2 g cm^{-2}, the protons require a much denser target than do the x-rays. Eichler and Vestrand[40] and Hillas[38] have suggested that protons accelerated at the neutron star have grazing collisions with the surface of the larger companion just before and after eclipse, providing a natural (although never completely quantitative) explanation for two regions of activity in the phase plot.

VI. Underground Muons. The situation changed dramatically early in 1985, when the Soudan and NUSEX groups independently reported evidence for underground muon signals from the direction of Cygnus with the characteristic 4.8 hr period. The Soudan group[7] initially reported an excess of 84 ± 20 counts in a phase plot of events accumulated between Sept. 1981 and Nov. 1983 (Fig. 18). The detector was the 31-ton 2.9 m x 2.9 m Soudan I concrete and proportional tube calorimeter located at a depth of 1800 meters water equivalent (corresponding to a muon threshold of 650 GeV at the earth's surface) in the Soudan Iron Mine in Minnesota. The measured flux was 7 x 10^{-11} $cm^{-2}sec^{-1}$, comparable to the gamma ray flux above 10^{12} eV (Fig. 15). The measured excess in the phase plot was centered at $\delta = 43.5°$, RA = 306.7°, 2.8° north of the known Cygnus X-3 position of $\delta = 40.8°$, RA = 307.6°. The

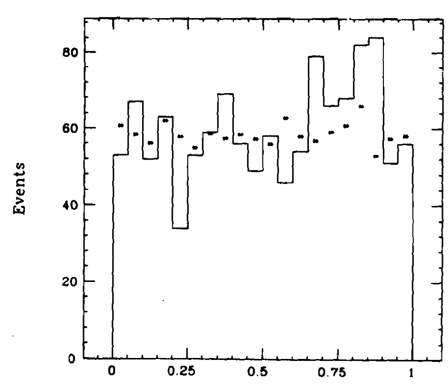


Fig. 18. Phase plot for underground muons at Soudan. Solid line shows observed data; points are the expected uniform background.

quoted angular resolution was 1.7° (taking into account both the instrumental resolution and possible errors in the absolute orientation of the detector). When the analysis was repeated for the cone of 3° width about the true direction of Cygnus X-3, the number of events in the peak was reduced to 60 ± 17 over the unusually broad range of phases 0.65 - 0.85 (Fig. 19; compare the much narrower phase plots of Fig. 16). Also shown in Fig. 19 is a phase plot of those events consisting of two muons, separated in time by 0.5 hrs or less, arriving from the direction of Cygnus X-3. A much stronger peak appears in this figure, but no convincing physical explanation has been suggested.

Depending on their assumptions about the expected phase and the shape of the background, Marshak et al.[7] suggest probabilities between 2×10^{-2} and 2×10^{-4} that their signal might be due to a random fluctuation in the background. Based on their published distributions, however, an rough independent estimate can be made of the relative likelihood L that their peak is due to a real source as compared to the probability that it is due to a statistical fluctuation: Of a total of 345 counts in their five-channel peak, they attribute 60 to a source and 285 to background (assumed to be flat). Using the prescription of ref. 41, the Poisson probability P_S can be calculated of the 345 counts being due to some background level B plus a source of strength S = 60, as compared to the probability P_B that the 345 counts are due entirely to the background B. Summing over all possible values of B with the condition that the best estimate for B is 285 events and taking the ratio L = P_S/P_B gives a relative likelihood L = 15: for a particular choice of channels in the phase plot, chosen a priori, it is 15 times more likely that the observed peak is due to the presence of a source superimposed on the background than that it is due to a background fluctuation. The phase region from 0.65 to 0.9 is not special (cf. Fig. 17); a peak could have occurred in any of M = 20 bins. Conservatively, however, there are 4 totally independent places to put a 5-channel wide peak, so M = 4 is probably a lower limit. This results in a confidence level 1 - M/L $\lesssim$ 73% that the enhancement is due to Cygnus X-3 rather than to a fluctuation in the background. This estimate overstates the statistical uncertainty in the background but understates the systematic uncertainty: Marshak et al.[7] have adopted a flat background, yet Ayres[42] has shown a plot of background as a function of right ascension at declinations away from the source which shows a peak in the phase plot similar to that in Fig. 19. Molnar[43] has raised similar statistical objections.

Fig. 19 also shows a comparison of the Soudan phase plots for 1981-1983 and for 1985 - 1986. The peak which shows up in 1981 - 1983 is totally absent in 1985 - 1986; this is interpreted by the experimenters as evidence that the source has turned off. Given the known time-variable behavior of the source in every other range, this may be possible; given the other difficulties with the results, however, the situation is far from satisfying.

At approximately the same time, the NUSEX group[8], using their 150-ton nucleon decay detector beneath Mt. Blanc in the Alps, have reported a similar underground muon signal, again modulated by the 4.8 hr phase from the direction of Cygnus. The NUSEX detector is deeper (5000 mwe, corresponding to a threshold muon energy at the earth's surface of 3.4 TeV) but of comparable size (3.5 m x 3.5 m x 3.5 m) to the Soudan detector. Between 6/1/82 and 2/1/85, they observed 32 events coming from inside a 10° x 10° window centered on the known position of Cygnus X-3 in the narrow phase bin between 0.7 and 0.8; 13 background events were expected (Fig. 20). Although the experimental resolution was 0.5° - 1°, the events were smeared out over a wide (10° x 10°) region of the sky (Fig. 21). The NUSEX group have plotted their results on a year-by-year basis (Fig. 22), and (like Soudan) see enhancements in 1983 and 1984, but nothing since 1984.

Battistoni et al.[8] quote a probability less than 10^{-4} that a background fluctuation in any bin might occur at a level equal to or greater than their observed peak, and the likelihood

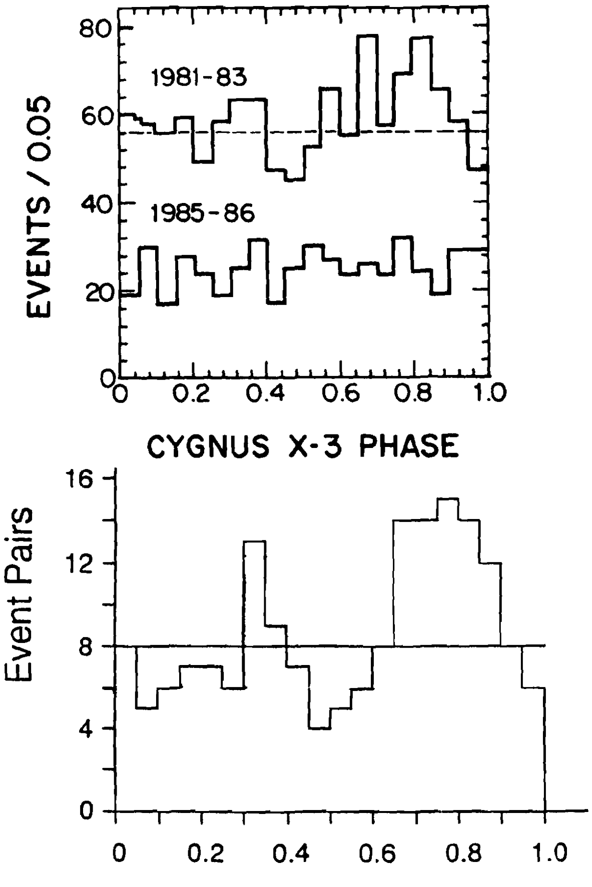


Fig. 19. Upper figure: Phase plots for Soudan muon events in 1981-1983 and 1985-1986. Lower figure: Phase plot for "high-rate" times, when two muons arrive from the direction of Cygnus within 0.5 hrs.

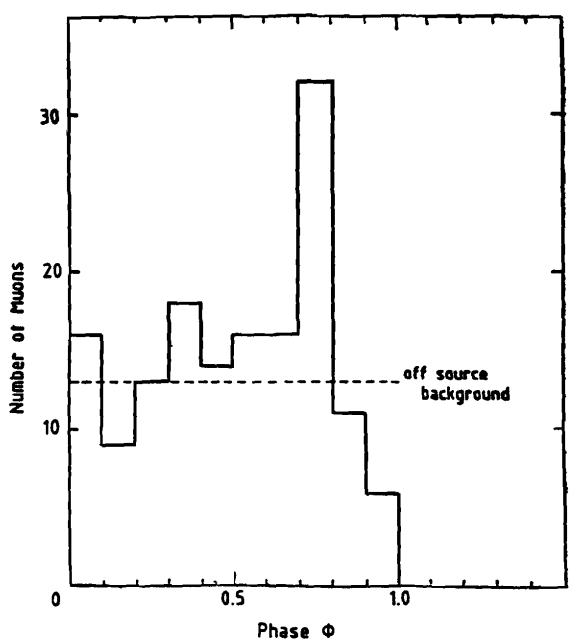


Fig. 20. NUSEX phase plot for 1982 - 1985.

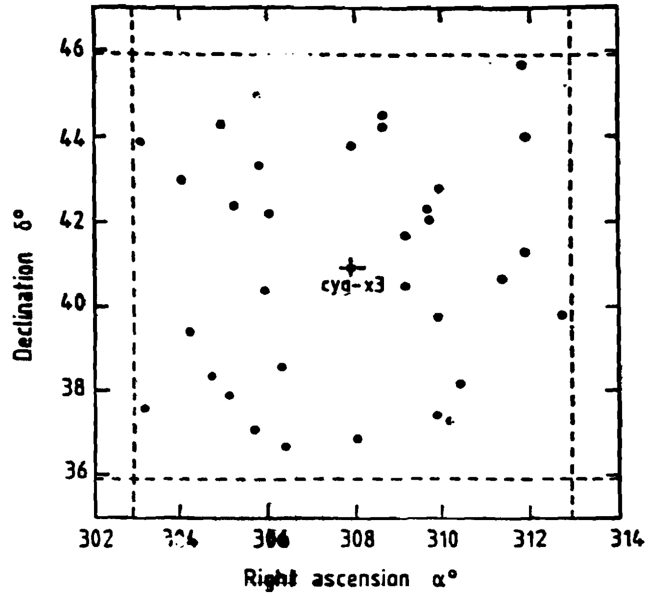


Fig. 21. Arrival directions of muons from the Cygnus region in the phase interval 0.7 - 0.8.

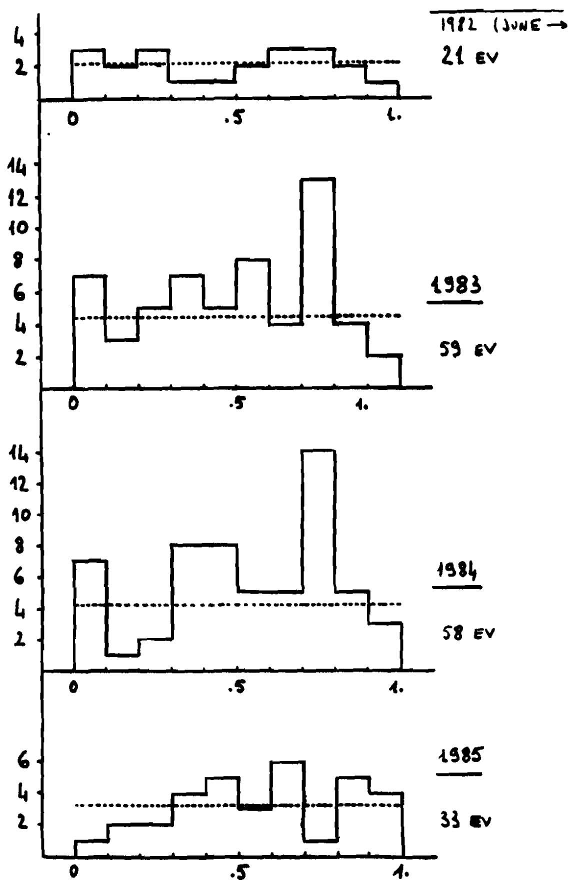


Fig. 22. Yearly NUSEX phase plots.

ratio calculated as above is reasonably high ($L \sim 50$). However, a peak at phase 0.7 - 0.8 is seen by no other experiment (Fig. 17) and is not special or expected in any way, so presumably a peak in any of M = 10 bins would have been acceptable. Even without allowing for the extra degrees of freedom introduced by opening up the angular window beyond the instrumental resolution, the confidence level becomes 1 - $M/L \lesssim 80\%$.

If the Soudan and NUSEX observations are correct, then there are profound particle physics implications[44]. The primary radiation must clearly be neutral in order to propagate in a straight line over the 11 kpc or more from Cygnus X-3 to the earth. Neutrinos are ruled out by the angular distribution: neutrinos would arrive from all directions equally, but the observed events have an arrival direction distribution similar to that of downward-moving atmospheric muons[8]. Neutrons are ruled out because they would decay at energies below 10^{18} eV; a sufficiently large flux of 10^{18} eV neutrons to explain these observations would have been detected elsewhere. If the primary beam is composed of gamma rays, then one must explain the surprising fact that the observed fluxes of 0.6 - 3 TeV underground muons are approximately equal to the fluxes of TeV gamma rays seen by atmospheric Cerenkov detectors. Cygnus X-3 gamma rays must therefore produce secondary TeV muons with essentially 100% efficiency, compared to the expected values[45] of 1 - 10% for muon energies 0.6 - 3 TeV. Starting with the γ-ray fluxes measured on the surface by Kiel and Haverah Park, Stanev et al.[45] calculate that they would have expected 0.4 high energy muons from Cygnus X-3 in the initial 0.9 yr Soudan exposure.

It has been suggested[44] that a totally new particle may be responsible for the observed underground signals. The NUSEX phase plot shows an enhancement in a narrow 30-min slice of the 4.8-hr period (Fig. 20). The smallness of this time dispersion δt sets a lower limit on the Lorentz factor of the primary particles: $\gamma^2 \gtrsim L/c\delta t$. If L = 11 kpc is the distance to Cygnus X-3, then $\gamma > 10^4$; if the energy of the NUSEX primaries is taken to be typically 10 times the muon threshold energy ($E_p \sim 50$ TeV), then the primary mass must be less than about 5 GeV. One is therefore left with the prospect of a long-lived (for $\gamma = 10^4$, $\tau_{rest} \gtrsim 10^8$ sec) 5 GeV neutral particle with a high muon production cross section which has been overlooked at accelerators.

Although a number of authors have discussed the possible implications of these observations at some length[44], there appear to be major difficulties in accepting the experimental results: As discussed earlier, the statistics are unfortunately much less compelling than they must be in order to support the kinds of particle physics conclusions described above; the Soudan phase peak is surprisingly broad, whereas the Cerenkov and air shower results all show much sharper peaks in the phase plots; and the NUSEX results in particular show an unexplained $10^{\circ} \times 10^{\circ}$ smear of arrival directions.

The most crucial criticism, however, comes from the fact that the Soudan I and NUSEX detectors are the smallest and least sensitive of several existing underground detectors. Yet none of the other detectors operating during 1982 - 1986 have been able to confirm the Soudan and NUSEX results. A summary of the flux limits in the phase interval 0.7 - 0.8 is shown in Fig. 23. (The Soudan results are given for the phase interval 0.65 - 0.9.) The very large Baksan[46] and Kamioka[47] detectors have set limits significantly below the level observed by Soudan, and the Homestake[48,49] and Frejus[50,51] limits are well below the NUSEX observation. Cutler and Groom [52] have recently reanalyzed their Mayflower Mine data from 1978 - 1983 (intensity-weighted depth 507 m.w.e.) for time periodicities, and find an excess at the Cygnus period at a flux level 3.1×10^{-8} $cm^{-2}sec^{-1}$ but at only a 2.3σ significance level.

The observation periods used for these points[51] are shown in Table 1. Frejus turned on in early 1984, but with less than full efficiency until 1985, and Homestake only began taking data early in 1985; so that it is certainly conceivable that these two detectors

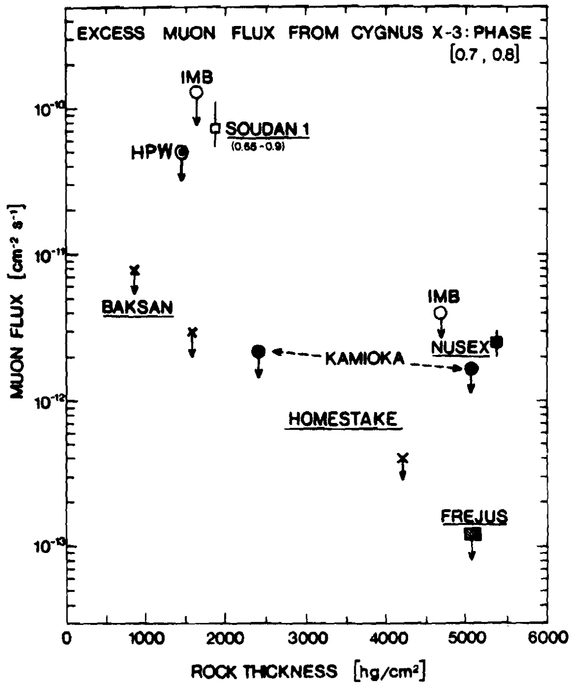


Fig. 23. Soudan and NUSEX results compared to the flux limits from other underground detectors.

could have missed a hot period in 1983 - 1984. The Baksan and Kamioka detectors were on the air in 1983 - 1984, however, and provide limits in marked conflict with at least the Soudan observation.

The Soudan and NUSEX groups have argued that their results suggest that the source was hot during 1983 - 1984, and has been quiet since then. In Oct. 1985, however, a very large radio flare occurred[29], with the 11 cm intensity exceeding 18 Jy. The Soudan group[53] have reported an excess flux of muons arriving from the direction of Cygnus X-3 during the time around the radio flare in the very narrow phase bin 0.725 - 0.750 (Fig. 24). Kamioka was not running at the time, and Homestake[49] and Frejus[51] saw nothing (Fig. 25). Soudan and Homestake are separated by only 300 miles, so that they were observing the source essentially simultaneously. If both the Soudan and Homestake results are correct, then the spectrum must have been so steep that the small, shallow Soudan detector (2.9 m x 2.9 m, 650 GeV) could see relatively low-energy events while the larger and deeper Homestake detector

Table 1.
Underground Observations of Cygnus X-3

	Observation period 81	82	83	84	85	86	Reference
Shallow detectors:							
Soudan I	—	—	—		—		Ref. 7
Kamioka			—	—			Ref. 47
HPW				—			Ref. 58
Baksan			—	—	—		Ref. 46 and Tignes (Jan '86)
Deep detectors:							
NUSEX		—	—	—			Ref. 8
Frejus				—	—	—	Ref. 50,51
Homestake					—	—	Ref. 48,49

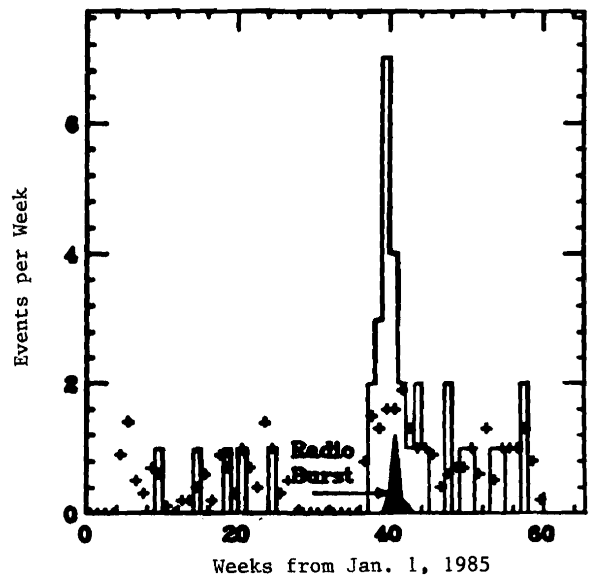


Fig. 24. Weekly event rate seen by Soudan during 1985 from a 5° cone around Cygnus X-3, in the phase interval 0.725-0.750. The time of the Oct 1985 radio flare coincides with the peak in the measured underground muon rate.

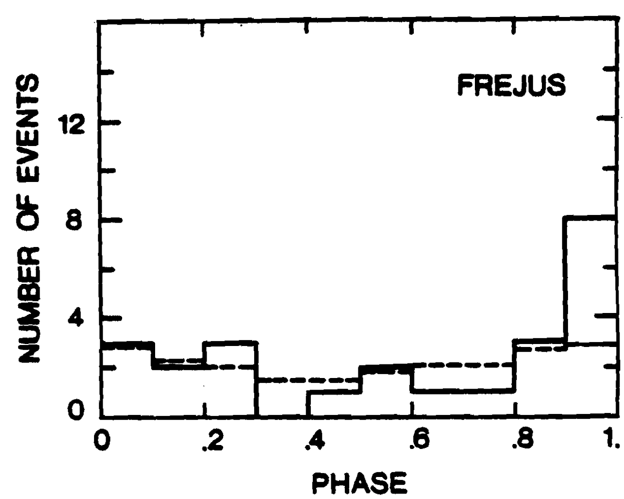


Fig. 25. Frejus phase plot during the interval Sept. 26 - Oct. 19, 1985, for a 5° cone around Cygnus X3. The dashed line gives the expected background rate.

(8 m x 16 m, 2.6 TeV) was unable to detect an excess flux of higher-energy events. Based on the assumption of an E^{-2} differential power-law spectrum for γ-rays at the surface and an E^{-3} differential spectrum for the secondary muons, scaling the observed Soudan rate to Homestake gives an expected 6 muons from Cygnus X-3 in the phase bin 0.7 - 0.8; 3 muons were expected from atmospheric background, and 3 events were observed.

Although the Soudan underground flare results have not been confirmed, an enhanced signal was apparently seen by the Baksan air shower array during the time of the Oct. 1985 radio flare[54], when excess counting rates of 3.5, 2, and 2 standard deviations were seen on the three successive days Oct. 14-16.

VII. Conclusions. There exist an abundance of observations at x-ray, radio, infrared, and γ-ray energies demonstrating clearly that Cygnus X-3 produces copious fluxes of photons at energies up to roughly 10^{16} eV. At high energies, it may produce a sizeable fraction of the total cosmic ray output of the galaxy, and its intensity varies significantly on time scales ranging from tens of seconds to months.

The Soudan and NUSEX underground results, if taken at face value, raise perplexing questions about both the source mechanism and the nature of the radiation. However, the statistics of the observations are in both cases far less than compelling, and the lack of confirmation from larger and more sensitive detectors operating at the same time provides strong evidence against an underground Cygnus X-3 effect.

On the other hand, if the Soudan and NUSEX workers are correct in invoking time variability in the emission (that is, if their positive signals occurred at times of high emission, if the contemporaneous Baksan and Kamioka observations somehow missed the effect for unexplained reasons, and if in addition the source then went into a low state as other detectors turned on), then one can expect the source to return to a high state on a time scale of months at most, if the x-ray and TeV γ-ray data are a reliable guide. In this case, in fact, the source is already a year or more overdue, so that it is difficult to be optimistic about this possibility.

As far as the yearly radio flares and the possibility of correlated high energy emission, a world-wide campaign of correlated radio and infrared observations has been organized[29] for the period around October, 1986. In the United States, the Soudan, IMB, and Homestake underground detectors; air shower arrays at Homestake and Los Alamos; and the atmospheric scintillation and Cerenkov detectors at Fly's Eye, Haleakala, Mt. Hopkins, and Homestake have all planned simultaneous observations during this period, as have underground and surface cosmic ray detectors elsewhere. (Disappointingly, as of early November, 1986, no large radio flare has yet been detected.)

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