# CYGNUS X-3: SOURCE OF VERY HIGH ENERGY GAMMA RAYS

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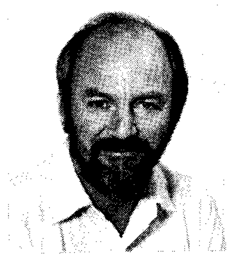

Abstract

Observations of TeV-PeV gamma rays from Cygnus X-3 using above ground air shower arrays and atmospheric Cherenkov detectors are summarized. The implications for theories of cosmic ray origins are discussed.

"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy"    Hamlet, W. Shakespeare.

Introduction

At all wavelengths Cygnus X-3 is an extraordinary object. Although it was one of the earliest x-ray sources discovered (Giacconi et al. 1967), it is still, after 20 years of research, one of the few strong x-ray sources about whose nature there is a major uncertainly. Conservative estimates of its distance place it on the edge of the galaxy and give it an x-ray luminosity that make it one of the strongest x-ray sources in the galaxy in the kev region. As such, it should be easy to identify with a class of objects which duplicate its properties. No other object quite matches Cygnus X-3 in its wide range of bizarre behavior; it is significant that it has been compared with such diverse objects as SS433, Circinus X-1 and Scorpius X-1. Its unusual properties are apparent at all wavelengths. It is extremely frustrating that one of the most interesting and powerful sources in the galaxy should lie so close to the plane that it is almost totally optically obscured. In the absence of optical observations, its true nature is a mystery; even the origin of its well-established 4.8 hour period is not unambiguous. It is generally assumed to be associated with orbital motion but without spectroscopic verification, this is only a hypothesis.

In the wide band stretching from the infrared to radio wavelengths, its chief characteristic is its variability. Although the infrared (H and K bands) show an underlying 4.8 hour periodicity (perhaps of thermal origin), the emission is generally sporadic and most likely non-thermal. Flares of as short as two minutes are observed together with outbursts lasting several hours.

If Cygnus X-3 was only a radio source, it would stand out as a highly unusual object. As figure 1 shows, it is liable to extraordinary increases in

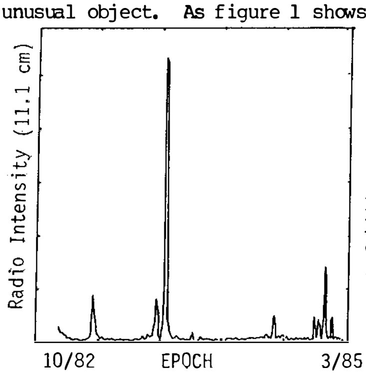


Figure 1. The radio flux from Cyg X-3 at 11.1 cm from Oct.,1982 to Mar.,1985 (Johnston et al. 1985) showing the large variations in intensity.

its radio output during which its radio flux increases to $10^3$ times its quiescent level. For a period of days at some wavelengths it is then one of the brightest radio sources in the sky. Other x-ray binaries have been observed to emit radio waves but none with the intensity of Cygnus X-3. It is one of the few sources that shows both quiescent radio emission and flares of high intensity; it is one of the very few galactic sources in which jets are observed. Conventional theories of the accretion process do not easily accommodate radio emission; the mechanism is almost certainly non-thermal and must point to the presence of high energy electrons or ions moving in a magnetic field. The spectral behavior of the radio flares in Cygnus X-3 is consistent with synchrotron radiation from the expansion of a cloud of relativistic electrons.

The gradual shift in time of the peak of the emission in the flares with increasing wavelength is characteristic of the synchrotron emission from radio jets in quasars; Hjellming has called Cygnus X-3 a "nano-quasar" on this account, the "nano" prefix arising from the fact that its intensity is only $10^{-9}$ times that of a conventional quasar. This picture of Cygnus X-3 as an emitter of jets of relativistic particles is confirmed by recent radio observations with the VLA (Geldzahler et al. 1983) which measure their spatial extent.

It was an unusual outburst of radio photons that led to Cygnus X-3 being the subject of one of the most extensive observing campaigns of any astronomical object. In the month following the September, 1972 outburst, Cygnus X-3 was observed at practically every major observatory and at wavelengths ranging from radio to TeV gamma rays (Hjellming 1973).

Even in x-rays, Cygnus X-3 defies precise definition. The assymetric 4.8 hour sine wave, the failure to display a complete eclipse, the variability from cycle to cycle, the quasiperiodic oscillations, the long term variations for which various periods have been suggested, all mark it as an unusual object. The peak luminosity make it one of the most luminous x-ray sources of any kind in the galaxy. At hard x-ray wavelengths, the spectrum changes dramatically with time.

In summary therefore, even ignoring the most important property of Cygnus X-3, its emission of photons of energy greater than 0.1 TeV (which is the subject of this review), it is one of the most puzzling sources in the galaxy. On the basis of its radio properties alone, it would be the prime candidate for investigation as a high energy particle source. As we shall see later, this very high energy gamma ray emission may be a common property of x-ray binaries with Cygnus X-3 unique only in its total luminosity. Such high energy particle acceleration has obvious implications for theories of cosmic ray origins.

Ground-based detection techniques.

To set the very high energy gamma ray observations of Cygnus X-3 in perspective, it is necessary to have some understanding of the detection techniques involved. These techniques are not new but they are relatively underdeveloped.

At photon energies above 1 kev the earth's atmosphere is equivalent in its absorbing power to a lead shield almost 1 m in thickness. Direct detection of very high energy gamma rays from the earth's surface, even at mountain altitudes, is therefore impossible. Satellite detectors are limited in size and hence in flux sensitivity; the high energy cutoff of the EGRET experiment on the Gamma-Ray Observatory (originally scheduled for launch in 1988) is 30 GeV and represents the effective high energy limit for the direct detection of gamma rays using current space technology.

The indirect detection of very high energy gamma rays from the earth's surface is possible if use is made of the products of the interaction of the gamma ray with the air molecules. For a primary energy of 1 PeV ($=10^{15}$eV), the resulting air shower at sea level can consist of 100,000 particles in a disk 1 m thick and 100 m in diameter. An array of particle detectors can determine the arrival direction of the shower by measuring the time of arrival of the shower front at each detector. Air shower arrays typically have an energy threshold of 1 PeV at sea level and 0.1 PeV at mountain altitude (3 km).

In addition to the particles in the shower front, there will be a disk of atmospheric Cherenkov photons radiated by the atmosphere as the relativistic particles traverse it and beamed in the direction of the primary trajectory. These optical photons can be easily detected using simple light receivers. The atmospheric Cherenkov technique is generally used in the 0.1 to 100 TeV energy range.

Note that the collection area in these experiments is not determined by the size of the individual detector elements (particle detectors or light receivers) but by the lateral spread of the secondary particles or tertiary optical photons. In these experiments the earth's atmosphere acts as the detection medium; in this respect this branch of photon astronomy is unique in actually demanding the presence of an atmosphere.

These detection techniques are remarkably simple but efficient. The collection areas are $10^4$ $m^2$ (photons) or $10^3$ $m^2$ (particles) and the angular resolution ~1-2$^{\circ}$. They do suffer from a large background of charged cosmic rays (amongst which the gamma rays are detected as directional and/or temporal anisotropies). This background can be reduced by the selection of showers whose properties match those of pure electromagnetic cascades (based on the muon-to-electron ratio at detector level, the shower age, or the distribution of

Cherenkov light). Although the earth's atmosphere has many advantages as a detector medium (thickness, scale-height, transparency, cost) it does suffer the disadvantage that it is not under the control of the experimenter who is limited by changes in pressure, temperature and transparency. After 30 years of experience these parameters are well-understood.

By the standards of high energy physics and space-borne astrophysics experiments, ground-based gamma-ray experiments are low budget and relatively unsophisticated. Being field experiments, they lack the control and calibration of laboratory experiments. They operate at energies that generally exceed those available in particle accelerators. Many of the particle array experiments were not purpose-built for gamma-ray astronomy. It is not surprising, therefore, that measurements of absolute fluxes show rather large deviations; there is no strong steady source of particles or photons that can be seen at all energies and that can be used as a standard candle to compare estimated sensitivities.

That these simple experiments should have succeeded in the detection of very high energy gamma rays from Cygnus X-3 is a remarkable example of cost effectiveness in a field where cost is often assumed to be paramount to importance.

TeV to PeV Gamma-Ray Observations.

The observation of 0.3 TeV to 10 PeV gamma rays from Cygnus X-3 has been reported by at least twelve different groups between 1972 and 1985. All of these groups made their observations using the atmospheric Cherenkov technique (ACT) or air shower arrays (ARA). Almost all of the groups reported one or more positive detections which were considered by the authors to be statistically significant in their own right i.e. had a significance equivalent to that of a 3 sigma effect or greater. While one may quibble with one or two of the published results on the grounds that the statistical significance is overstated, this does not effect the overall conclusion from the general body of observations that the emission of gamma rays from the direction of Cygnus X-3 has been observed. Most of the photons are modulated with the 4.8 hour period of Cygnus X-3 but with a light-curve unlike that seen at lower energies and which varies in amplitude and shape.

A synthesis of the observations, listed in Table 1, either in terms of light-curve or energy spectrum is difficult for a variety of reasons: (i) energy thresholds, collection areas, flux sensitivities, etc., are not well determined as outlined in the previous section; (ii) many of the observations are at different epochs; because of the small duty-cycle of the ACT and the limited number of experiments this is particularly true at TeV energies; (iii) some of the results are of limited statistical significance; (iv) the published light-curves, particularly prior to 1981, have often been folded using different values of P and $\dot{P}$. Since 1981, most gamma-ray observers have used the quadratic values given in van der Klis and Bonnet-Bidaud (1981) (hereafter vdK-BB). It is possible that the actual variation is more complicated than that given since individual measures of the x-ray ephemeris often deviate widely. Several longer term periodicities have been suggested, including a 4.95 hour variation in the radio band (Molner et al. 1984).

In general the published detections indicate emission around phase 0.2 (when the x-ray source emerges from its partial eclipse) and around phase 0.6 (the time of x-ray maximum). In some cases, emission is seen at both phases.

Because the 4.8 hour period of Cygnus X-3 is almost one-fifth of a day, care must be taken to ensure that solar modulations do not introduce pseudo-periodicities into the data base. In the case of air shower arrays this can be checked by searching at other periods that are fractions of a day e.g. 4, 6, or 8 hours. The two minute advance in phase per sidereal day means that in two weeks of observation, the observations taken in a given phase bin that is only 0.1 wide will include the same zenith angle. Air shower thresholds change with zenith angle and hence background measurements must always be made at the same zenith angle to measure the real background. This is almost invariably done so that it is very difficult to see how a systematic effect could introduce the narrow phase effects reported.

In Table 1, the various observations are summarized by group, the epoch of the observations, the energy threshold, the phase of maximum emission and reference. The observations are clustered by energy: (a) 0.1 to 10 TeV (b) 10 to 500 TeV (c) 100 TeV to 10 PeV. Broadly speaking the observations in (a) which all used the ACT have the greatest reliability; those in (b) where the techniques are mixed are the least reliable.

The most important results are discussed below:

(a) TeV observations in the USSR; 1972-80.

These observations were made with simple atmospheric Cherenkov detectors consisting of two or three 1.5 m aperture mirrors on a single mount. The observations were taken in the drift-scan mode i.e. the earth's rotation swept the field of view of the detectors through the position of the source which was apparent as an increase in counting rate compared with the rate before and after the source was in the field of view. In this way, the observations were taken at the same zenith angle and systematic changes were monitored by comparing the rates before and after transit of the source. These experiments were carried out at the Crimean Astrophysical Observatory (CAO) and at Tien Shan in eastern Russia.

The first detection of TeV gamma rays came a few days after the announcement of the giant radio outburst of September 2, 1972 as part of the world-wide campaign to observe Cygnus X-3 in this unusual high state. The results of these first few months of observations were reported in the Proceedings of the 13th International Cosmic Ray Conference at Denver, USA in 1973 (Vladimirsky, Stepanian and Fomin (1973)). However, since the paper was not presented orally at the conference and since the results were not included in the special 1973 edition of Nature Physical Science that was devoted to results obtained during the outburst, the TeV gamma-ray results were largely ignored, at least in the Western Hemisphere.

Unfortunately, this initial lack of interest in the CAO observations which were statistically significant, was to extend to the subsequent CAO and Tien Shan observations for the rest of the decade. These USSR observations, taken with detectors whose sensitivity did not change over eight seasons of observations, constitute the largest and most impressive data base of TeV observations of Cygnus X-3. Unfortunately there is no single publication which presents the details of all the observations although they have been summarized (Stepanian 1982; Stepanian 1983) and reviewed (Weekes 1985a).

Fig. 2 shows the composite light-curve over the eight years from the CAO

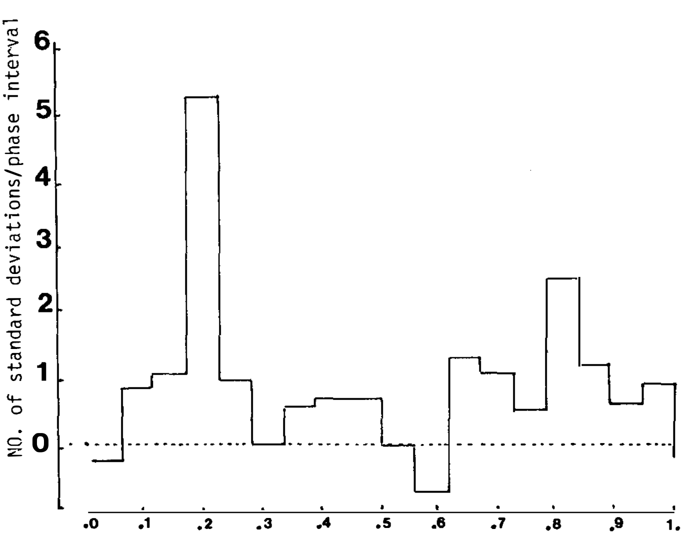


Figure 2. The 4.8 hour light-curve of Cygnus X-3 at TeV energies in which the excess from the source direction is plotted as standad deviations per 1/12 phase bin. The net excess is at the 3.9 sigma level based on observations from 1972-80 (Stepanain et al. 1982).

Table 1

Published Detections of Cygnus X-3

| Group | Location | Epoch | Energy (TeV) | Phase of Max. Emission | | Reference |
|---|---|---|---|---|---|---|
| (a) 0.1 to 10 Tev | | | | | | |
| Crimean Astrophysical Observatory | Crimea | 1972 | 2 | 0.2 | 0.7 | Vladim. et al.(1973) |
| | | 1973 | 2 | 0.2 | 0.7 | |
| | | 1974 | 2 | 0.2 | | " (1975) |
| | | 1975 | 2 | 0.2 | | Stepanian et al(1977) |
| | | 1979 | 2 | 0.5 | | Neshpor et al (1980) |
| | | 1980 | 2 | T | | Fomin et al (1981) |
| Lebedev Phys. Inst. | Tian Shan | 1977-78 | 5 | 0.2 | 0.8 | Mukanov (1981) |
| Whipple Observatory Coll. | Whipple Obs. Arizona | 1980 | 1 | 0.6 | | Weekes et al. (1981) |
| | | 1981 | 0.3 | T | | Weekes et al. (1982) |
| | | 1983 | 0.6 | 0.6 | | Cawley et al. (1985) |
| ISU-JPL -UC | Edwards AFB California | 1982 | 0.5 | 0.6 | | Lamb et al. (1982) |
| U. Durham | Dugway, Utah | 1982-83 | 1 | 0.6 | | Gibson et al. (1982) |
| | | 1984 | 1 | 0.6 | | Chadwick et al.(1985) |
| (b) 10 to 500 Tev | | | | | | |
| Nuclear Res. Lab. | Gulmarg, India | 1976-77 | 500 | 0.6 | | Bhat et al. (1985) |
| U. Utah | Dugway, UT | 1983 | 500 | 0.2 | | Baltrus. et al(1985b) |
| | | 1985 | 500 | T | | Elbert(this workshop) |
| Torino | Platau Rosa, Italy | 1982 | 30 | 0.2 | 0.6 | Morello et al. (1983) |
| Institute of Nuclear Research | Baksan, U.S.S.R. | 1984 | 100 | 0.6 | | Alexeenko et al(1985) |
| (c) 0.1 to 10 PeV | | | | | | |
| Univ. of Kiel | Kiel W. Germany | 1976-80 | 1000 | 0.2 | | Samorski and Stamm (1983) |
| Univ. of Leeds | Havarah Park, U.K. | 1978-82 | 1000 | 0.25 | | Lloyd-E. et al(1983) |
| | | 1984 | 1000 | 0.6 | | Lambert et al(1985) |
| Univ. of Tokyo | Akeno Ranch, Japan | 1981-84 | 1000 | 0.6 | | Kifune et al (1986) |

obsevations. Three features of this result should be emphasized

(1) There is a net excess (3.9 sigma) from the direction of the source irrespective of phase.

(2) The data is folded with the 4.8 period that was derived from the gamma-ray observations by alignment of the peak around phase 0.2. This independent measurement of the 4.8 period (and period derivative) is in agreement with that derived from the x-ray observations.

(3) During the course of the observations the light-curve was not constant i.e. there were times when emission at the later phases was more significant than that around phase 0.2.

The general features of this result were verified by a quasi-independent experiment at Tien Shan which was operated from 1977-79.

The principal results from these experiments are summarized below:

(1) a periodic component of TeV gamma rays is detected from Cygnus X-3 with an average intensity of $1.6 \times 10^{-11}$ photons-$cm^{-2}$-$s^{-1}$.

(2) the emission is concentrated in narrow phase intervals corresponding to the emergence from x-ray eclipse, the x-ray maximum and the entrance of x-ray eclipse.

(3) there is also a sporadic component which is unrelated to the 4.8 hour period and which persists for some days.

(4) the gamma-ray emission may correlate with the radio outbursts.

Since 1980, there have been no atmospheric Cherenkov observations of Cygnus X-3 in the USSR as the CAO and Tien Shan groups are building new, and more sensitive, detectors.

(b) TeV Observations in the USA., 1980-83.

Three independent experiments observed Cygnus X-3 in the TeV energy range using different versions of the atmospheric Cherenkov technique between 1980 and 1983. These experiments lacked the coverage of the USSR results, but they produced results that were remarkably similar although individually they did not have the statistical significance of the USSR results.

The first completely independent confirmation of the USSR result came from a joint Smithsonian Astrophysical Observatory-University College, Dublin experiment at the Whipple Observatory in southern Arizona in 1980. Using two 1.5 m reflectors in coincidence, an excess was seen at phase 0.6-0.7 using the vdK-BB ephemeris (Weekes et al. 1981). During this period of observations (April-June 1980) Cygnus X-3 underwent a major change in x-ray activity; the gamma-ray light curve was taken when Cygnus X-3 was near the peak of its x-ray activity ( fig. 3(a)). These observations, as well as subsequent observations at the same site, provide evidence for variability in the light-curve on time scales of months (Cawley et al. 1985).

Two 11 m Solar Concentrators were used as atmospheric Cherenkov detectors by a joint Jet Propulsion Laboratory-University of California at Riverside-Iowa State University collaboration to detect Cygnus X-3 at energies of 0.5 TeV and above in August-September 1981 (Lamb et al. 1982). The drift-scan technique was

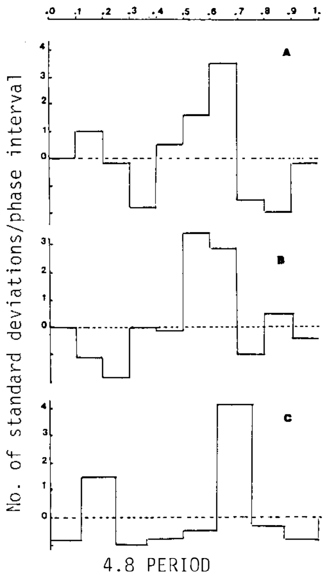


Figure 3. The 4.8 hour light-curves of Cygnus X-3 in TeV gamma rays as seen in three experiments in 1980-83. The ordinate is in standard deviations per hase bin. (a) Whipple Observatory (Weekes et al. 1981); (b) Edwards A.F.B. (Lamb et al. 1983); (c) Dugway (Dowthwaite et al.1983). The deficits could be caused by excess emission from the galactic plane around Cygnus X-3 (Dowthwaite et al.1985).

used but fast timing between the two separated detectors was used to preferentially select showers coming from the center of the field of view (and hence from the direction of the source during transit). An enhancement was seen when Cygnus X-3 was at the center of the field of view; when these event times were folded with the vdK-BB ephemeris, the light-curve shows a peak in the phase interval 0.6-0.8 at the 4.4 sigma level. The light-curve is shown in fig.3(b).

The University of Durham (United Kingdom) group operated an array of four atmospheric Cherenkov telescopes at the Dugway Proving Ground in Utah, USA from 1981 to 1984. Each telescope consisted of three 1.5 m aperture detectors which were operated in coincidence. More than 350 hours of observation of Cygnus X-3 were obtained in 1981 and 1982 in both the drift scan and tracking mode of observation. The combined results are shown in fig. 3(c); there is evidence for substructure (as short as three minutes) also (Dowthwaite et al. 1983). Subsequent observations of the general distribution of emission in the galactic plane near Cygnus X-3 suggest that the distribution may be non-uniform and that Cygnus X-3 may lie in a hollow in the plane (Dowthwaite et al. 1985). This would have the effect of increasing the significance of all drift-scan or ON/OFF observations (Chadwick et al. 1985) but as the effect has not been confirmed, it should be treated with caution.

These three experiments provide evidence for an active phase in the TeV gamma-ray emission centered on phase 0.6 to 0.7. However, it is clearly not steady emission and the Durham group have suggested a 19.2 day modulation. At the peak of this modulation they see evidence for a statistically significant 12.59 ms periodicity. If confirmed this result would be extremely important as it would provide the first direct evidence for the presence of a fast pulsar within the system and hence provide a vital clue to the acceleration processes involved. However atmospheric Cherenkov detectors are liable to various sources (man-made and natural) sources of optical contamination so that it is important that the periodicity be seen elsewhere, preferably with a non-optical technique.

In these simple atmospheric Cherenkov experiments there is no evidence obtained about the nature of the primaries which have been assumed to be (and are consistent with) gamma rays. More sophisticated atmospheric Cherenkov telescopes (Weekes 1985b; Hillas 1985) will be able to make this distinction.

(c) PeV observations: 1976-1984.

Three air shower experiments have reported evidence for the emission of gamma rays with energies of 1 PeV or above from Cygnus X-3. Air shower arrays, like atmospheric Cherenkov telescopes, are limited by the cosmic ray background; detection at high energies implies that the source spectrum is not steeper than the background spectrum. It is generally assumed that most source emission spectra will steepen with increasing energy. These experiments were not originally designed to do gamma-ray astronomy; all are close to sea level and hence are sensitive only to primaries above 1 PeV. Taken together, the three experiments are consistent with the detection of PeV gamma rays from Cygnus X-3 but there are some apparent inconsistencies that point to source variability, and shower or detector parameters that are not completely understood.

The first report of the detection of PeV gamma-ray emission from any source came from the University of Kiel group (Samorski and Stamm, 1983) who had operated an air shower array at Kiel from 1976-80. The shower arrival direction was determined in this array with unusually high accuracy (+/- $1.5^{o}$). The data base was first culled to select only those showers with age parameter, s > 1.1; these showers corresponded to older and hence early developing, showers such as those initiated by an electron or gamma ray. The arrival direction of each shower was sorted into bins of right ascension and declination. A band of right ascension (in $4^{o}$ bins) centered on declination $40.9^{o}$ (the declination of Cygnus X-3) was plotted as in fig. 4; the bin centered on Cygnus X-3, the

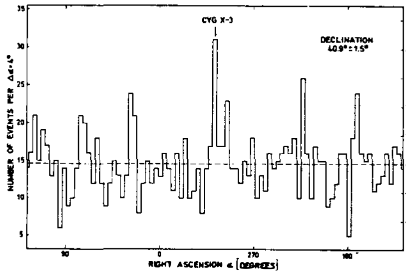


Figure 4. Number of events per bin in declination band that includes Cygnus X-3 (Samorski and Stamm, 1983).

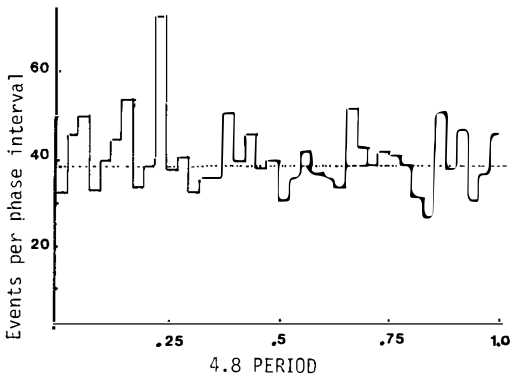


Figure 5. Data from Haverah Park folded with the 4.8 hour period. The ordinate is events per 1/40 phase bin (Lloyd-Evans et al. 1983).

primary target of the search, showed a 4.4 sigma excess. Subsequently all the sky visible to the array was examined but the distributions were within statistics. When the data within this bin were folded with the vdK-BB ephemeris, a light-curve was obtained that had a small excess at phases 0.1 to 0.3. When the data was analyzed with the period derivative reduced by its statistical error, this excess was 2.5 sigma at phase 0.2 to 0.3 (Samorski and Stamm 1985). Considering the small number of events, these light-curves should not be over analyzed.

The controversy about the Kiel result does not stem from its statistical significance but rather from the nature of the particles detected. When the data in the Cygnus X-3 bin is examined in terms of its muon-to-electron ratio, it is found to be only slightly less than that obtained from a typical proton shower (0.77 $\pm$ 0.09) whereas the expected ratio would be ~ 0.10. This discrepancy could be understood if (a) more muons are produced in electromagnetic cascades at high energies (b) incomplete shielding of the muon detectors allowed some punch-through (c) the shower was initiated by a primary other than a gamma ray.

The detection of a PeV signal from Cygnus X-3 was confirmed by the University of Leeds group within a few months of the publications of the Kiel results (Lloyd-Evans et al. 1983). A subset of the Haverah Park array was operated between 1978 and 1982 with an energy threshold of 1 PeV. The muon-to-electron ratio was not measured in this experiment and the angular resolution was ~ +/- 3$^{o}$. When all events were sorted by arrival direction, there was a 1.7 sigma excess in the bin centered on Cygnus X-3. When these events were subjected to a periodicity analysis with the vdK-BB ephemeris, the light-curve shown in fig. 5 was obtained. The peak at phase 0.225-0.25 is at the 5 sigma level; it is the narrowest feature seen at any gamma-ray energy. It is difficult to see how such a sharp feature could be an artifact in data spread over four years. The Haverah Park data show a cut-off at energies above 10 PeV. More recent observations from Haverah Park with a new array with improved sensitivity show a small signal at phase 0.63 (Lambert et al. 1985). Since neither the age parameter nor the muon-to-electron ratio was measured in the Haverah Park results, the signals do not bear directly on the nature of the primaries.

The Akeno Ranch Air Shower Experiment is operated by the University of Tokyo and employs a wide variety of detectors so that many shower parameters are measured. Data taken between 1981 and 1984 have been searched for evidence of a signal from Cygnus X-3. Only weak evidence for emission is found but that is in data selected to have a very small muon-to-electron ratio. A peak in the light-curve (folded with the vdK-BB ephemeris) is seen near phase 0.5; the significance of the detection is estimated as $2x10^{-3}$, considerably lower than that of the Kiel and Haverah Park results. The chief interest in this result is that, if real, it points to gamma rays as the shower progenitors and hence counteracts the conclusion introduced by the Kiel result.

New, and more sensitive, air shower experiments, which include large muon detectors, are now on-line in a number of countries so that definitive results on PeV gamma rays from Cygnus X-3 should shortly be available.

Energy Spectrum.

Given that there is strong evidence for variability and that emission at different portions of the light-curve may have different spectra, it is not easy to plot a meaningful energy spectrum. Fig. 6 shows an integral energy spectrum with data taken over many different epochs and averaged over many different periods of observation. It is obvious that the spectrum is very flat (compared with the observed cosmic ray spectrum) and can be fitted by a power law exponent of -1.1.

Chardin and Gerbier (1986) have argued that a spectrum of this sort is just what would be expected if the signal arose from statistical fluctuations at all energies. However, put another away, this is the spectrum that would be

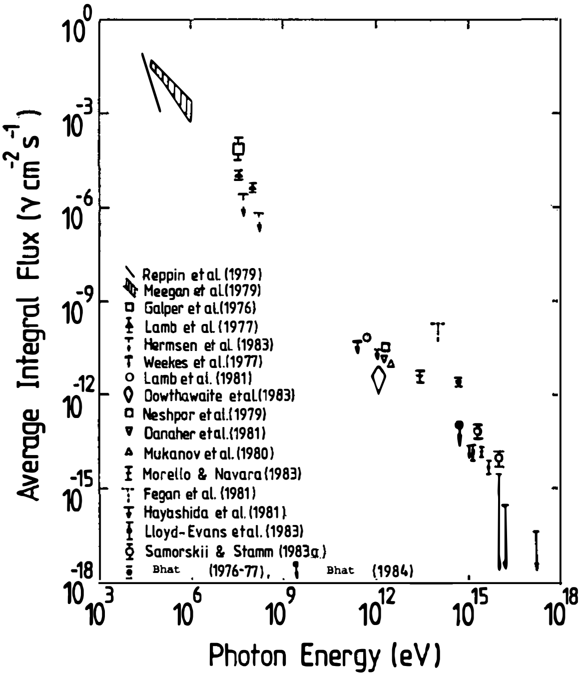


Figure 6. Composite of gamma-ray measurements from Cygnus X-3 from 1972 to 1984, derived from Bhat et al. 1985.

expected if small, but statistically significant, signals were detected with current techniques in the TeV-PeV energy range. If the signals were significantly larger than this, then they would have been apparent in previous general all-sky surveys of the Northern Hemisphere. The fact, that they were not, limits the luminosity that might be expected. If they were any smaller than the measured values, then obviously they would not be detected and there would be no energy spectrum to dispute! Hence, given that the detected signal is most likely to be close to noise, there is only a small range of spectral indices that are expected. It is exactly this reasoning that led to low expectations of the detection of a signal at PeV energies and hence the absence of experiments specially designed to do gamma-ray astronomy at PeV energies.

The energy spectrum of Cygnus X-3 is of more than academic interest. At energies close to 1 PeV it is expected that photon-photon pair production (on the microwave photons from the $3^{\circ}$ black body background) will cause an absorption dip, which, if measured, would have a number of interesting implications. It would be the first direct verification of the photon-photon interaction, it would verify that the $3^{\circ}K$ field extends to the source, it would give a measure of the distance to the source and perhaps most important at this instant, it would verify that the primary quanta were indeed gamma rays.

Time Variability.

For many physicists the most disturbing aspect of the detection of very high energy gamma rays from Cygnus X-3 is the clear indication that the signal is variable with time. This illustrates the fundamental difference between high energy physics and high energy astrophysics. In physics the fundamental parameters are constants which are always verifiable. In astrophysics the only constant is that most of the observed phenomena are not constant! Verification is still necessary but is often difficult because it must come at a later epoch and perhaps from another analogous source.

That the observed emission from an x-ray binary should vary in amplitude, in phase or even in frequency, is not unique to these wavelengths or to this source. The sources that populate the universe of the high energy astrophysicist are anything but constant. The degree of variability often increases with the energy of photon observed. In x-ray astronomy sources vary by factors of $10^4$ in amplitude; their time variations may range from milliseconds to years and the form of the variation can be periodic, quasi-periodic, transient or completely irregular. It would be naive to think that this kind of variability would not also be seen at gamma-ray energies; in fact, there are a number of reasons to believe that it would be more pronounced at the highest energies.

Very high energy gamma rays are inevitably the by-product of the interaction of very high energy particles (ions or electrons) within the sources. It is notoriously difficult to accelerate particles to energies in excess of 1 TeV in man-made accelerators. Even using our most sophisticated 20th century technology, it is difficult to maintain the conditions necessary for efficient particle acceleration. It is hard to conceive of a natural particle accelerator which would act like a standard candle.

The target material (the beam dump) is also a variable which must increase the fluctuations in the gamma-ray beam. In the chaotic conditions of cosmic sources (particularly those in which accretion is the driving energy source) a steady flux of gamma rays must be the exception rather than the rule.

The only cosmic source where we can directly monitor the production of high energy particles is the sun. Nobody could expect the flux of gamma rays produced in solar flares to be a standard candle. It could be that cosmic particle production takes place as a series of flare-like outbursts.

Cygnus X-3 is known to be variable at every wavelength at which it can be monitored. The radio outbursts, which only last for days, are separated by years of inactivity and represent increases of intensity of factors of $10^3$ to

$10^4$. Flaring activity is also seen in the infrared. The long term x-ray behavior is shown in fig. 7 as 10-day averages observed by a Vela satellite. If the x-ray detectors were less sensitive or if the source was further away, then only the flux above the dotted line might be seen; in this case the 4.8 hour modulated signal would be sporadic and not unlike the signal seen at TeV energies. An improvement in detector sensitivity by a factor of ten would dramatically change this picture.

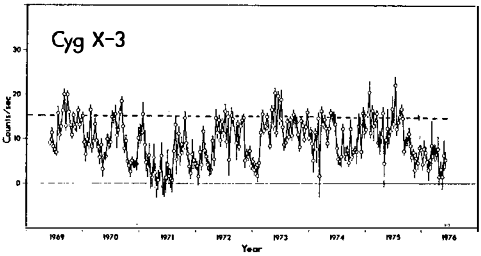


Figure 7. X-ray measurements (3-12kev) from Cygnus X-3 plotted as 10-day averages from 1969-76 as seen by the Vela 5B satellite (Priedhorsky and Terrell,1986).

As we shall see below, the gamma-ray observations suggest that Cygnus X-3 is an extremely powerful source of cosmic rays. A source of this luminosity would not be expected to persist for long; Hillas (1985) has suggested a lifetime of 100 years meaning that the source is evolving rapidly. Bhat et al. (1985) have suggested that there may be evidence for a secular decrease in gamma-ray intensity. The evidence for this decrease is still rather sketchy and the conclusion does not seem justified. A secular decrease should also be seen in x-rays.

Other sources.

There is increasing evidence that Cygnus X-3 is not alone as an x-ray binary producing very high energy gamma rays. A recent catalog of observed TeV or PeV sources (Ramana Murthy 1985) lists twelve sources including the Crab and Vela pulsars, the Crab Nebula and Centaurus A. Since not all of these have been independently verified, the list must be treated with some caution.

The binary x-ray sources that have been seen at TeV or PeV energies are listed in Table 2. While those at the top of the list can be considered as well established, having been seen by one or more groups, the others await confirmation. Observations on Hercules X-1 and 4U0115+63 are discussed in another paper at this Workshop (Weekes, 1986).

The existence of other very high energy gamma-ray sources (albeit weaker ones) increases confidence in the Cygnus X-3 detection which led to their discovery.

Table 2

TeV-PeV Observations of X-ray Binaries (excluding Cygnus X-3)

| Source | Energy | Technique | Group | Epoch | Reference |
|---|---|---|---|---|---|
| Her X-1 | TeV | AC | Univ. of Durham | 1983 | Chadwick et al. (1985) |
| | TeV | AC | Whipple Obs.Coll. | 1984 | Gorham et al. (1986) |
| | PeV | AC | U. of Utah | 1983 | Baltrus. et al.(1985a) |
| 4U0115 +63 | TeV | AC | Crimean Ast. Obs. | 1971-73 | Stepanian et al. (1975) |
| | TeV | AC | Univ. of Durham | 1984 | Chadwick et al. (1985) |
| | TeV | AC | Whipple Obs. Coll. | 1985 | Lamb et al. (1986) |
| Vela X-1 | PeV | PA | Mt. Chacaltaya Coll. | 1964-66 | Suga et al. (1985) |
| | PeV | PA | Univ. of Adelaide | 1982-83 | Protheroe et al. (1984) |
| LMC X-4 | PeV | PA | Univ. of Adelaide | 1982-83 | Protheroe and Clay (1985) |
| Cen X-3 | PeV | PA | Mt. Chacaltaya Coll. | 1964-66 | Suga et al. (1985) |

Cosmic Ray Luminosity.

Apart from the implication of hitherto unsuspected modes of particle acceleration in binary x-ray sources, the astrophysical importance of the detection of very high energy gamma rays from Cygnus X-3 arises from the implied total luminosity in high energy particles. The flat energy spectrum (figure 6) means that at the highest detected energies (1-10 PeV) the gamma-ray luminosity is comparable with the x-ray luminosity in the keV region. The particle luminosity must be even greater.

The gamma ray luminosity $L_g$ is obtained from the expression:

$$L_g = 4\pi d^2 . e . F_g$$

where $F_g$ = the observed gamma-ray luminosity between 1 and 10 PeV in ergs $-cm^{-2}-S^{-1}$

d = distance to the source in cm

e = absorption correction

From the air shower experiments $F_g = 10^{-10}$ $erg\text{-}cm^{-2}\text{-}s^{-1}$. The distance is not easy to measure. The best distance estimates rely on optical measurements which are not possible for Cygnus X-3. During the large radio flares, the 21 cm absorption feature can be measured with high accuracy and the presence of intervening hydrogen clouds (HI regions) can be detected as they will be Doppler-shifted relative to the rest frame. Using models of the galaxy, the position of these regions can be estimated. In the Cygnus X-3 direction there are six known HI regions; absorption features are seen from all six, meaning that Cygnus X-3 must be beyond the farthest (Dickey 1983). On a conservative model of galactic structure, in which the distance to the galactic center is 10 kpc, this distance, a lower limit, is 11.6 kpc. There is no upper limit from these measurements; hence Cygnus X-3 is at the edge of the galaxy or beyond. By its similarity with galactic sources, it seems unlikely that Cygnus X-3 is extra-galactic and hence this distance is usually assumed. It should be stressed however that on this galactic model this is a lower limit.

The importance of the distance measurement is that it directly effects the photon-photon pair production absorption correction (Gould 1984; Cawley and Weekes 1984; Protheroe 1985). For the minimum distance, e ~ 3.

With these values, $L_g = 6x10^{36}$ ergs $cm^{-2}s^{-1}$. As the gamma rays are the secondary products of higher energy particles (most likely ions), we can estimate the luminosity of 10-100 PeV protons necessary to produce the gamma rays. The most likely process is proton-proton interactions producing neutral pions which decay to gamma rays; the efficiency of such production is not greater than 10%.

Since the observed light-curve is modulated in an unusual way, a model must be constructed to explain the periodic variation. The most popular model is that proposed by Vestrand and Eichler (1982) in which protons are emitted isotropically by the compact source (neutron star or black hole) and gamma rays are produced only when the particle source is aligned with the atmosphere of the companion star. Since the beaming arises from the target, the particle luminosity is greater than the gamma-ray luminosity by the inverse of the observed gamma-ray duty cycle (0.05 to 0.10).

The total particle luminosity (10-100 PeV) is then > $6x10^{36}$ x 10 x 10 ~ $6x10^{38}$ $erg\text{-}cm^{-2}\text{-}s^{-1}$.

Hillas (1984) has estimated the flux of particles required to keep the observed cosmic ray flux in equilibrium as 2 x $10^{37}$ $ergs\text{-}cm^{-2}\text{-}s^{-1}$. Cygnus X-3 is thus more than sufficient to supply the entire galaxy. Since it is unlikely that this is a unique source, the implication is that it must evolve rapidly.

The particle production can be significantly reduced if the particle production is beamed. There are as yet no completely satisfactory models of Cygnus X-3 and the full significance of the discovery of the gamma-ray emission for theories of cosmic ray origin must await such models. However, it seems likely that there is a direct link between the production of high energy particles in x-ray binaries and the observed cosmic radiation.

Discussion

Reports of a new phenomena such as the emission of high energy quanta from Cygnus X-3 deserve critical scrutiny. Chardin and Gerlier (1986) and Molner (1986) have recently expressed some reservations about the validity of some of the claimed detections of Cygnus X-3. Some of their criticisms may be valid but because a small number of the reported observations are doubtful, it does not follow that the phenomena is not real. The sheer number of "non-statistical" observations reported from the direction of Cygnus X-3 is difficult to explain in any other way than in the detection of high energy photons. Short of an international conspiracy, an unconscious boot-strapping or a most unlikely series of coincidences this seems the most likely hypothesis.

More and better observations are urgently needed and fortunately these should soon be forthcoming. An improvement in sensitivity by even a factor of 2 or 3 should settle the issue.

The above ground experiments say little about the nature of the detected particle, particularly at lower energies. There is thus little that can be said about the underground detections except to note that the two reported detections are not consistent with the gamma-ray flux measurements.

I am grateful to Drs. Chardin and Molner for preprints of their work and to several colleagues for critical discussions particularly Drs. M. F. Cawley and R. C. Lamb.

The work is supported by the U.S.D.O.E.

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