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High-energy gamma-ray and hard X-ray observations of Cyg X-3

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Summary. High-energy (70 MeV $< E <$ 5 GeV) gamma-ray observations of Cyg X-3 by the ESA satellite COS-B and hard X-ray (14 keV $< E <$ 140 keV) observations by the Leiden-MIT balloon experiment, Leimit, are presented.

COS-B viewed the Cygnus region 7 times between 1975 November and 1982 February. A search for steady gamma-ray emission from Cyg X-3 and for emission pulsed at the characteristic 4.8 h period did not reveal the source. Combining the ~ 300 days of COS-B observations the 2σ upper limit on the 70 MeV–5 GeV flux is 9.7 10^{-7} ph cm^{-2} s^{-1} for the phase interval in which modulated X-ray emission has been detected, and ~ 1.0 10^{-7} ph cm^{-2} s^{-1} for the phase intervals for which gamma-ray emission above $\sim 10^{12}$ eV has been reported.

Leimit observations of Cyg X-3 in 1979 May show the 4.8 h modulation with sinusoidal light curve and modulation depth of ~ 0.30, measured earlier at lower X-ray energies, for energies up to ~ 140 keV.

A comparison with, and a study of earlier results over the 14 decades in energy from 1 keV up to $\sim 10^{17}$ eV indicates that the strong variability of Cyg X-3 over more than one order of magnitude at energies below 20 keV does not exhibit itself in the data collected at hard X-ray energies, and the power emitted per decade of energy reaches a minimum in the MeV–GeV region. If the primary gamma-rays up to 10^{15} eV originate close to the central source, absorption by the keV X-rays in the Cyg X-3 binary system could explain the latter phenomenon.

Key words: Cygnus X-3 – gamma rays: sources – X-rays: sources: binaries – COS-B

1. Introduction

Cyg X-3 is a source which has been extensively studied over the entire electromagnetic spectrum. In particular, the reported weak signal from Cyg X-3 at ultra-high-energy ($E \gtrsim 10^{14}$ eV) gamma rays (Samorski and Stamm, 1983; Lloyd-Evans et al., 1983; Kifune et al., 1985) and the claims of detections of muon-rich showers from Cyg X-3 (Marshak et al., 1985; Battistoni et al., 1985; Bartelt et al., 1985) make this a unique and enigmatic object, which has been proposed to be one of the most powerful emitters of charged cosmic-ray particles in the Galaxy (Wdowczyk and Wolfendale, 1983; Hillas, 1984).

After the discovery of Cyg X-3 by Giacconi et al. (1967) its X-ray emission was found to be modulated (Parsignault et al., 1972) with a very stable period of 4.8 h up to the hard X-ray range ($E \lesssim 80$ keV; Pietsch et al., 1976; White and Holt, 1982; Dolan et al., 1982; Willingale et al., 1985). The same modulation was detected in its infrared emission (Becklin et al., 1973), but not in its radio emission. However, the source exhibits erratic, frequency-dependent radio outbursts (see e.g. Woodsworth, 1983), making it at times one of the strongest radio sources in the sky (e.g. Gregory et al., 1972). Furthermore, Molnar et al. (1984) and Molnar (1985) reported from observations at several radio wavelengths that the radio emission in its low state may be interpreted as arising entirely from the superposition of a series of flares with a 4.95 h period in the flare timing.

In the MeV–GeV region the situation is confusing. The first claim of detection of periodic emission was based on only 15 excess counts ($E > 40$ MeV) in a phase histogram, using the data from two balloon flights (Galper et al., 1976). However, McKechnie et al. (1976) failed to see the source in their balloon measurements and placed an upper limit well below the value of Galper et al. The SAS-2 team (Lamb et al., 1977) reported a satellite detection of the modulated flux ($E > 35$ MeV) at the level of the upper limit given by McKechnie et al., but later observations by the COS-B satellite did not reveal the source (Bennett et al., 1977; Swanenburg et al., 1981; Hermsen, 1983).

The first reports of detection of periodic very-high-energy ($E \gtrsim 10^{12}$ eV) gamma-ray emmission from Cyg X-3 were made by the Crimean Observatory group (e.g. Vladimirsky et al., 1973; Stepanian et al., 1977; Neshpor et al., 1979), and several other

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groups confirmed the detection (e.g. Mukanov et al., 1979; Danaher et al., 1981; Lamb et al., 1982; Dowthwaite et al., 1983; Cawley et al., 1985). In most cases, the 4.8 h phase histograms show an excess in the phase intervals 0.2–0.3 and/or 0.5–0.7 (where the minimum in the sinusoidal X-ray light curve defines phase 0). Chadwick et al. (1985) claim to have detected within the TeV emission the long-sought-for fast pulsar in the Cyg X-3 system, with a period of ~12.59 ms, possibly confirmed by the Haleakala and the Whipple Observatory collaborations (for a discussion see Ramana Murthy, 1986). The ultra-high-energy ($E \gtrsim 10^{14}$ eV) gamma rays show excesses for the same phase intervals of the 4.8 h light curve (Samorski and Stamm, 1983; Lloyd-Evans et al., 1983; Kifune et al., 1985).

In this paper we show in Sect. 2 results from an analysis of Leimit (Space Research Leiden – MIT Collaboration) balloon measurements in the hard X-ray range, presented in a preliminary form by Van den Akker and Vermeulen (1983), and we discuss the spectrum and light curve at these energies in view of the partly conflicting earlier reports. In Sect. 3 we present a timing and spatial analysis of the complete set of COS-B gamma-ray observations of Cyg X-3 and compare our findings with those reported from SAS-2. In Sect. 4 we discuss the likely shape of the Cyg X-3 spectrum from 1 keV up to 10^{17} eV, discuss the spectrum in relation to some published models explaining very-high-energy gamma radiation and examine the impact on the spectral shape of gamma-ray absorption in the MeV–GeV region by soft X-rays.

2. The hard X-ray observations and results

During a balloon flight from Palestine, Texas, on 1979 May 14, 15 the Leimit hard X-ray telescope (Ballentine, 1981) observed Cyg X-3 for almost 4 hours at ~4 g cm^{-2} residual atmosphere with a NaI Phoswich-type scintillator telescope. The telescope had an effective geometric area of 1475 cm^2, and was sensitive over an energy range 15 keV $< E <$ 200 keV with an energy resolution of 17% at 60 keV. It consisted of two modules (each had a collimator with a field of view of 3° × 3° FWHM), which observed alternately the source and background regions for 128 s such that both regions were continuously monitored. The pointing system reached an accuracy of $\lesssim 0\overset{\circ}{.}1$. Cyg X-3 was observed between $1\overset{\mathrm{h}}{.}33$ and $5\overset{\mathrm{h}}{.}13$ GMT on 1979 May 15. This interval was briefly interrupted for detector calibration and an in-flight performance test.

2.1. *The 4.8 h modulation*

The total observation of Cyg X-3 covered slightly less than one complete 4.8 h cycle, but lasted sufficiently long to verify for the first time that the modulation is present up to energies ~140 keV. Light curves for the 20–40 keV, 40–80 keV, and 80–140 keV energy intervals, show that the modulation is present in each case (Van den Akker and Vermeulen, 1983). Figures 1 and 2 show curves fitted by sinusoidals of the form $A_0 + A_1 \sin\,(2\pi (t - T_0)/P)$, for the energy intervals 20–40 keV, 40–140 keV, and 20–140 keV to optimize the statistics. The parameters A_0, A_1, and T_0 are free parameters in the fit and the period P is derived from the ephemeris determined by Van der Klis and Bonnet-Bidaud (1981) from the extensive COS-B X-ray observations in the 2–12 keV band. The derived T_0 values are consistent with the value predicted by the ephemeris within the 1σ uncertainty. The ratio A_1/A_0 is a measure of the amount of modulation of the signal from Cyg X-3. The derived values (given in Figs. 1 and 2) are consistent with a constant value over the total 20–140 keV band ($A_1/A_0 = 0.30 \pm 0.08$). Bonnet-Bidaud and Van der Klis (1981) and Van der Klis and Bonnet-Bidaud (1982) derived ratios of about 0.25–0.45 from the COS-B 2–12 keV X-ray observations where the lower half of this range corresponds to a low state of Cyg X-3, and the upper half to a high state; the latter was probably the case during the Leimit observation (White and Holt, 1982). Similar values have been published by Dolan et al. (1982) for the 23–73 keV band using OSO-8 data.

Additional evidence for modulation in the hard X-ray range up to ~60 keV was given by White and Holt (1982), using Einstein MPC data ($E <$ 20 keV) taken when Cyg X-3 was in a very low state and HEAO 1 A-2 observations ($E <$ 60 keV) obtained during a high state. The general trends of the modulation agree remarkably well. Willingale et al. (1985) analysed EXOSAT ME data ($E <$ 50 keV), and claimed that the ratio A_1/A_0 decreases from 0.35 at ~5 keV down to $\lesssim$0.1 at 40–50 keV, but this decrease should probably be ascribed to particle-induced background counts in the data of the EXOSAT Xenon detectors, as supported by a re-analysis selecting those ME detectors which are least sensitive to this background (A. Smith, SSD/ESA, private communication).

A balloon measurement (50 keV $< E <$ 400 keV) by Meegan et al. (1979) over part of one cycle, phase 0.45 to 0.92, showed a

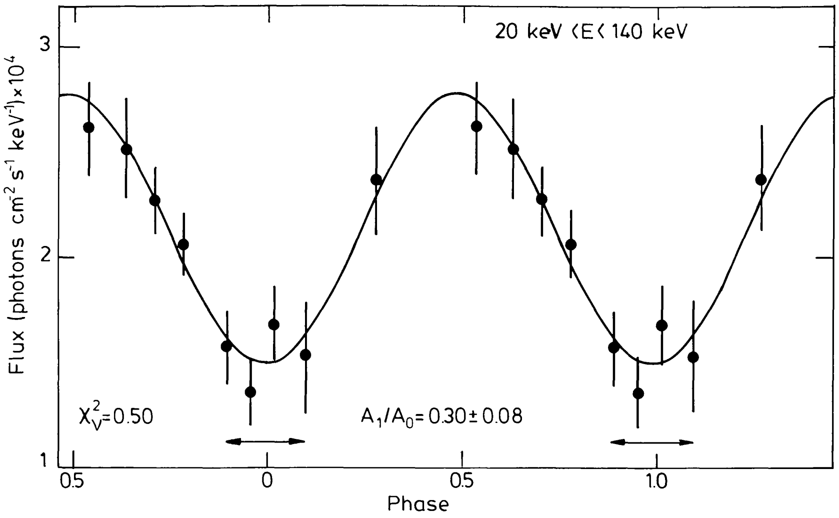

Fig. 1. Light curve of Cyg X-3 in the energy interval 20–140 keV measured with the Leimit hard X-ray telescope. Best-fit sinewave to the data is indicated; the ratio of the amplitude (A_1) and mean flux (A_0) and the reduced χ^2 are given in each case. The arrows indicate the background interval selected for calculating gamma-ray upper limits

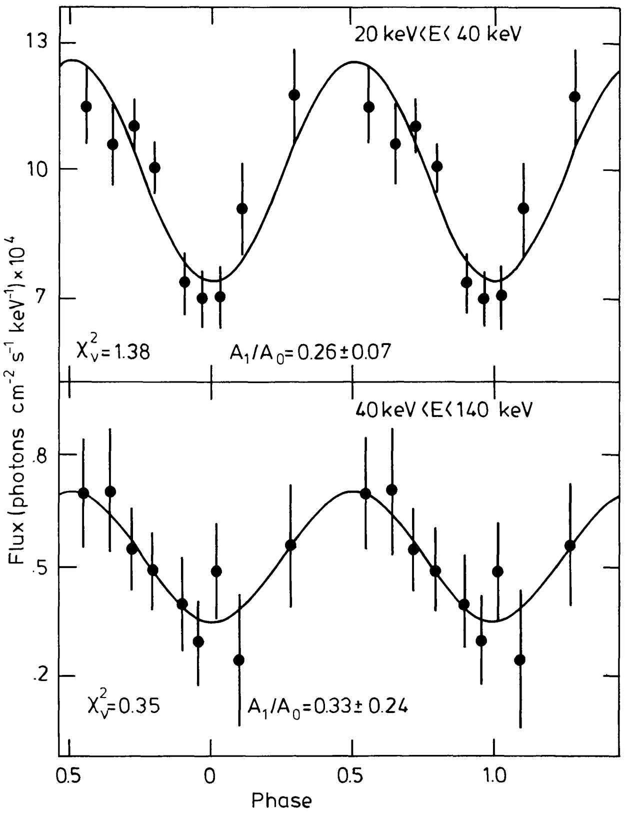

Fig. 2. Light curves of Cyg X-3 for two energy ranges presented as in Fig. 1

roughly linear flux increase over that phase interval, which is in contradiction with the HEAO 1 A-2 and Leimit findings. However, the field of view was ~13° FWHM, and Meegan et al. noted the possibility that the increase was due to a large increase in the flux from Cyg X-1. Such an effect would also explain their deviating spectrum, as discussed below.

2.2. *X-ray spectral analysis*

The best power-law fit ($C_1 E^{-\gamma}$) to the Leimit spectrum (14–140 keV) is given by

$$\frac{dN}{dE} = (40.3^{+17.6}_{-10.1})\, E\,[\mathrm{keV}]^{-(3.19^{+0.11}_{-0.07})}\ \mathrm{photon\ cm^{-2}\,s^{-1}\,keV^{-1}} \quad (1)$$

(1σ errors) and has $\chi^2 = 0.69$ (Fig. 3). A 16% correction for the incomplete coverage of the 4.8 h cycle was applied, normalizing the observed total flux to the parameter A_0, determined for the 20–140 keV range. There is good agreement with the previous results included in Fig. 3, with the exception of the spectrum presented by Meagan et al. (1979) (recall also their difference in temporal behaviour). Since their $\gamma = 2.2$ is identical to the value they present for their Cyg X-1 spectrum, it seems that the detected signal is indeed due to variability of Cyg X-1.

The Leimit spectrum is also consistent with the average OSO-8 spectrum, and the absolute fluxes ($E \gtrsim 30$ keV) measured by OSO-7 (Ulmer et al., 1974), and two more balloon flights (Pietsch et al., 1976; Voges et al., 1977), not included in Fig. 3. The deviating spectrum presented by Willingale et al. (1985) is also not shown in Fig. 3, because the re-analysis of the same EXOSAT data, using an improved calibration of the Xenon detectors and a more careful rejection of background counts, renders a consistent spectrum (A. Smith, SSD/ESA, private communication).

Apparently, the large time variability measured at energies $\lesssim 20$ keV (one order of magnitude or more), is not present at higher X-ray energies, although variability at the 10–30% level cannot be excluded. Reppin et al. (1979) reported time variability (a 30% flux decrease over 1.5 h), but this can be discounted and ascribed to the 4.8 h modulation if the ephemeris of Van der Klis and Bonnet-Bidaud (contempory with the balloon measurement) is used. The measured countrates listed in the HEAO 1 A-4 source catalogue (Levine et al., 1984) suggest time variability of 30% to 50% around their average rate, but Levine et al. pointed out that the total systematic uncertainty in the conversion from countrate to flux is of the same order of magnitude; the average level is consistent with the Leimit data.

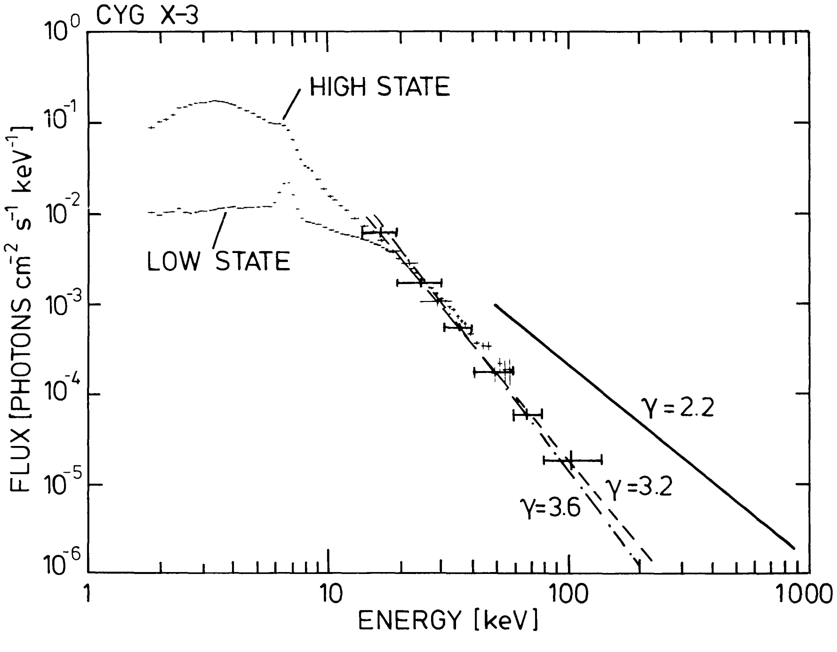

Fig. 3. Deconvolved spectrum of Cyg X-3 giving the hard X-ray fluxes measured with the Leimit telescope together with the spectrum from White and Holt (1982) (+) from HEAO 1 A-2 and Einstein SSS data. The latter spectrum is representative for the high and low state of Cyg X-3 between 2 keV and 60 keV. The best power-law fit to the Leimit data ($\gamma = 3.2$) and to the spectra of Reppin et al. (1979; $\gamma = 3.6 \pm 0.3$) and Meegan et al. (1979; $\gamma = 2.2 \pm 0.2$) are indicated

Table 1. Parameters of the relevant COS-B observation periods

Observation	Start date			End date			Pointing direction		Exposure Cyg X-3 (70 MeV–5 GeV)
	yr	m	d	yr	m	d	$l(°)$	$b(°)$	(cm^2 s)[a]
4	1975	11	28	1975	12	24	73.9	0.3	3.7 10^7
22	1977	6	8	1977	7	15	84.1	0.5	5.9 10^7
36	1978	11	3	1978	12	11	84.7	0.5	4.4 10^7
51	1980	5	14	1980	6	24	80.0	−0.2	4.0 10^7
55	1980	10	17	1980	11	4	71.2	0.4	1.1 10^7
60	1981	6	3	1981	7	24	85.6	−7.8	2.9 10^7
63	1981	11	3	1982	2	18	80.3	−1.2	7.9 10^7

[a] assuming an E^{-2} input spectrum and correcting for deadtime and sensitivity variations over the time in orbit

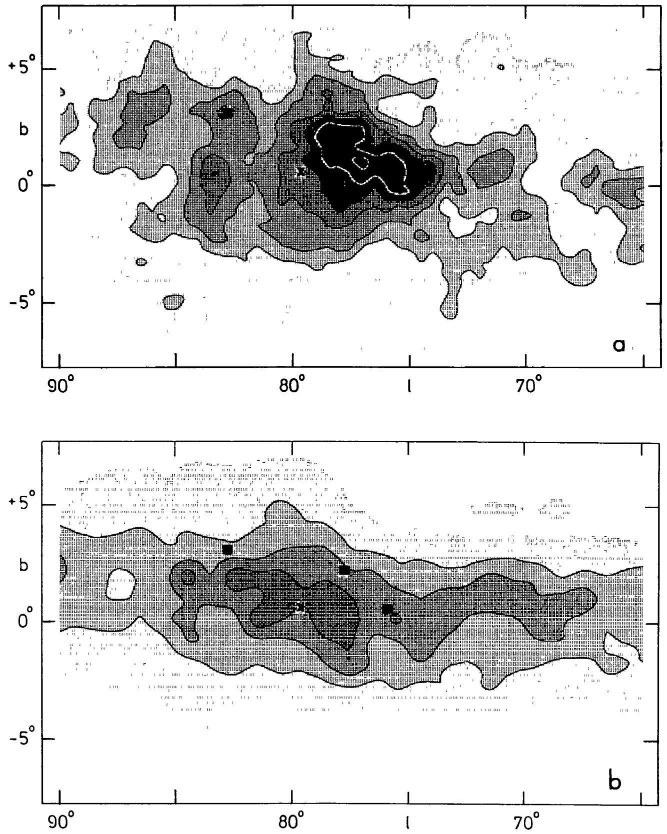

Fig. 4a and b. Gamma-ray intensity ($E > 500$ MeV) distributions in the Cyg-X region. Contour levels: 4, 6,..., 12, 14 10^{-5} photons cm^{-2} s^{-1} sr^{-1}, first step in grey scale at 2 10^{-5} photons cm^{-2} s^{-1} sr^{-1}. **a** Measured by COS-B; **b** Estimated using the total-gas distribution derived from HI and CO data and the model for the distribution of the cosmic-ray particles by Bloemen et al. (1986). ■ Position of gamma-ray sources not explained by the gas (Pollock et al., 1985). × Cyg X-3 position

3. The high-energy gamma-ray observations and results

The ESA gamma-ray (50 MeV < E < 5 GeV) satellite COS-B had Cyg X-3 within its field of view during 7 observation periods (Table 1) between 1975 November and 1982 February for in total ~300 days. The individual arrival directions and energies of the accepted gamma rays were derived with the well-established procedure first outlined by Scarsi et al. (1977).

The COS-B observations show a broad complex structure in the Cyg-X region (Mayer-Hasselwander et al., 1982). Figure 4a presents a skymap using data for $E > 500$ MeV of all seven periods (at these energies COS-B has its best angular resolution, < 1° FWHM). The major part of the emission probably originates in the interstellar medium from the interaction between cosmic-ray particles and the interstellar gas (Sect. 3.2). No evidence was found for a gamma-ray source at the position of Cyg X-3 in previous searches (Hermsen et al., 1977; Swanenburg et al., 1981). Since a weak signal could be hidden in the structured diffuse emission, the data were searched for the 4.8 h timing signature (Bennett et al., 1977) without obtaining a positive detection. In the following we apply methods that improve the source-detection threshold for both, the timing analysis and the spatial analysis, and we use all COS-B data available (Table 1). We do not attempt to detect the ~12.59 ms period reported by Chadwick et al. (1985), because the accuracy of the claimed period is not sufficient for a meaningful search in the COS-B data.

3.1. *Timing analysis*

For each COS-B observation, the arrival times of gamma-ray photons originating from a small, energy-dependent, region around the position of Cyg X-3 have been folded with the 4.8 h period, using the ephemeris derived by Van der Klis and Bonnet-Bidaud (1981). The photons were selected using the algorithm proposed by Özel and Mayer-Hasselwander (1983), which optimizes the signal-to-noise ratio taking into account the COS-B instrumental point-spread function and the structure of the underlying diffuse gamma-ray background. The event selection and folding were performed separately for different energy intervals (70–150 MeV, 150–300 MeV, and 300–5000 MeV), because the COS-B point-spread function is energy dependent (the angular resolution increasing with energy). The resulting phase histograms (Fig. 5) were summed to obtain the distribution for the integral 70 MeV – 5 GeV range. The "source" samples consisted of the events measured in regions of ~114 square degrees (70–150 MeV), ~73 square degrees (150–300 MeV) and ~11 square degrees (300–5000 MeV) around the position of Cyg X-3. Background samples were selected for each observation and folded with the 4.8 h period. These background samples contain about one order of magnitude more counts than the source samples. For each observation period the phase histograms for the background and the source samples are consistent with flat distributions (the χ^2-values are given in Table 2).

Upper limits on the modulated emission are primarily a function of the expected duty cycle. Table 2 gives upper limits for three selected phase intervals: 0.1–0.9, 0.2–0.3, and 0.5–0.7. The first interval corresponds to the X-ray emission (see Fig. 1); for the latter two intervals, most detections above 10^{12} eV have been reported.

Cyg X-3 was in a higher state of X-ray activity during some portions of the COS-B observation periods (Van der Klis and Bonnet-Bidaud, 1982). During observation period 51 Cyg X-3 was in a high state most of the time, but in periods 22 and 36 this was the case for only ~6 days. The gamma-ray photons during these 6-day intervals were folded separately, but no sign of the 4.8 h period was found. Caraveo et al. (1985) searched in the COS-B data for flaring of Cyg X-3 down to the scale of 1 day, but no evidence of such was found.

3.2. Spatial analysis

In the early searches for gamma-ray sources (Hermsen et al., 1977; Swanenburg et al., 1981) little information was available on the detailed structure of the diffuse gamma-ray emission in the galactic plane, originating from the interaction between cosmic-ray particles and the interstellar gas. In particular, large-scale CO surveys tracing the molecular gas were lacking, but these are available now, and have been used to construct a realistic model of the diffuse background (Lebrun et al., 1983; Bloemen et al., 1986). Pollock et al. (1985a, b) searched for gamma-ray sources superimposed on this modelled diffuse emission. They concluded that the gamma-ray distribution in the Cyg-X region can be explained as being the sum of diffuse emission and three pointlike gamma-ray sources, but none at the position of Cyg X-3, as depicted in Fig. 4 for energies above 500 MeV.

We used the likelihood method of Pollock et al. (1985a, b) to estimate the flux (upper limit) of a point source at the position of Cyg X-3, in addition to the diffuse emission and the two nearby sources (for three energy intervals). We optimized this procedure as far as possible, treating the intensity of the diffuse component and the source fluxes as free parameters, but no evidence for the detection of Cyg X-3 was found; Table 3 gives 2σ upperlimits.

3.3. Comparison with previous results

The COS-B upper limits are significantly lower than the flux levels reported by the SAS-2 team, $(10.9\pm3.1)\ 10^{-6}$ photons cm^{-2} s^{-1} for $E>35$ MeV and $(4.4\pm1.1)\ 10^{-6}$ photons cm^{-2} s^{-1} for $E>100$ MeV (Lamb et al., 1977). This disagreement between the SAS-2 and COS-B results needs further examination, because the SAS-2 and COS-B measurements of the gamma-ray flux and intensity distribution of the total excess in the Cyg-X region agree well given the statistics. Lamb et al. (1977) attributed in their analysis this *total* excess to Cyg X-3, concluding that the flux is 100% modulated with the 4.8 h period. However, the present knowledge of the interstellar gas distribution (discussed above) leads to the prediction of a significant gamma-ray excess originating in the large amount of molecular hydrogen in the Cygnus arm. A possible enhancement of cosmic rays in spiral arms (e.g. Parker, 1966) would imply an even larger Cyg-X excess than predicted in Fig. 4b; in fact, a slight enhancement by a factor of 2 would already raise the predicted flux above the flux observed from the total Cyg-X region, and would not be consistent with the two-dimensional distribution. The fraction of the gas column density that is located beyond the Cygnus arm is relatively small, so uncertainties in the cosmic-ray density at these large distances are of minor importance. It seems inevitable to conclude that at least half of the observed gamma-ray excess in the Cygnus-X region is of diffuse origin. The two COS-B sources 2CG075+00 and 2CG078+01, which contribute $\lesssim 50$% of the total excess, are detected in all 7 COS-B observations between 1975 and 1982, and appear to be constant over these ~6 yr (variability <30%; Pollock et al., 1985a). The assumption that the sources existed a few years earlier during the SAS-2 observations, seems to be justified, and agrees with the measured extent of the SAS-2 excess [the total excess in the SAS-2 data ($E>35$ MeV) is due to ~42 events, too few for a detailed two-dimensional analysis]. If the above argument is indeed correct, then the background level in the SAS-2 phase histogram has to be increased by at least 50% due to diffuse emission and by $\lesssim 50$% due to other sources, each of the two contributions rendering the claimed detection statistically insignificant. We point out to the reader that the SAS-2 team does

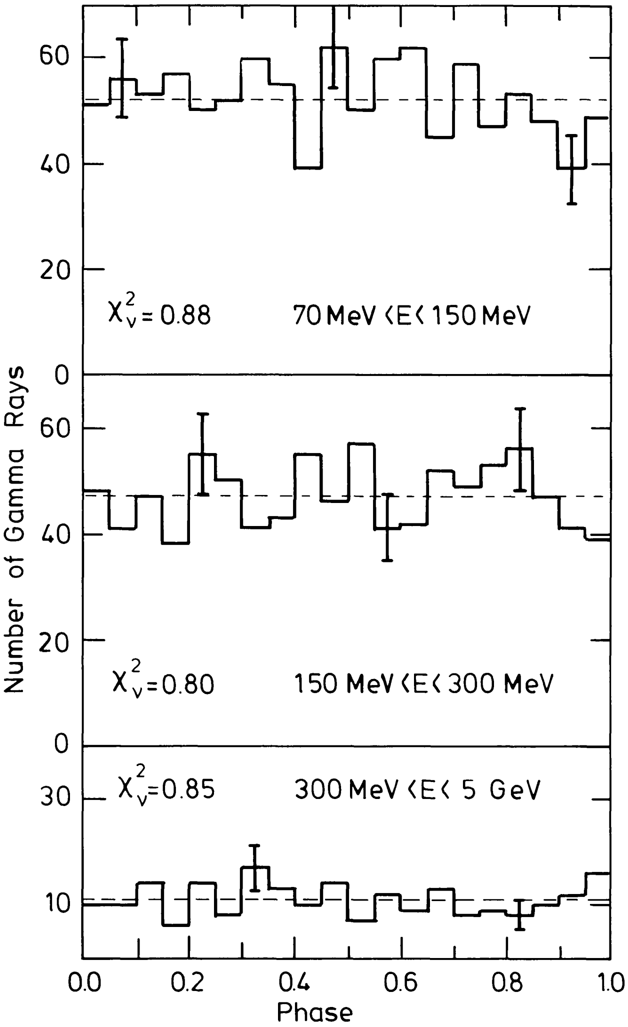

Fig. 5. Phase histograms of the arrival times, folded modulo ~4.8 h period, of gamma rays originating from a region centered on Cyg X-3 (see text) for three energy intervals. Data from 7 COS-B observation periods are used. The average levels and the reduced χ^2 values with respect to these levels are given

Table 2. Reduced χ^2 values for 20-bin phase histograms for background (bg) and "source" (s) samples, and 2σ upper limits (photons cm^{-2} s^{-1}) to the modulated (4.8 h) flux from Cyg X-3 for three selected (see text) phase intervals

Observation number	$\chi^2_{v,bg}$	$\chi^2_{v,s}$	2σ upper limits[a] (70–5000 MeV) for phase intervals		
			0.1–0.9	0.2–0.3	0.5–0.7
4	0.69	0.80	1.8 10^{-6}	3.0 10^{-7}	2.8 10^{-7}
22	1.05	1.87	2.1 10^{-6}	4.3 10^{-7}	4.6 10^{-7}
36	0.76	0.31	1.9 10^{-6}	3.9 10^{-7}	3.8 10^{-7}
51	1.21	0.73	2.1 10^{-6}	4.6 10^{-7}	2.4 10^{-7}
55	1.11	0.75	2.1 10^{-6}	0.9 10^{-7}	5.0 10^{-7}
60	0.79	1.22	3.0 10^{-6}	1.9 10^{-7}	2.2 10^{-7}
63	0.64	0.50	1.1 10^{-6}	2.5 10^{-7}	0.4 10^{-7}
All observations, 70–5000 MeV			9.7 10^{-7}	1.0 10^{-7}	1.1 10^{-7}
All observations, 70–150 MeV			1.0 10^{-6}	9.5 10^{-8}	2.2 10^{-7}
All observations, 150–300 MeV			7.3 10^{-7}	1.1 10^{-7}	1.2 10^{-7}
All observations, 300–5000 MeV			1.7 10^{-7}	4.0 10^{-8}	4.4 10^{-8}

[a] Assuming an E^{-2} spectrum in the energy range 70–5000 MeV

Table 3. 2σ upper limit to the total time-averaged gamma-ray flux from Cyg X-3 using the data from all COS-B observations of the Cyg-X region

Energy range	2σ upper limit[a]
70–150 MeV	7.5 10^{-7} photon cm^{-2} s^{-1}
150–300 MeV	6.5 10^{-7} photon cm^{-2} s^{-1}
300–5000 MeV	4.5 10^{-7} photon cm^{-2} s^{-1}

[a] Assuming an E^{-2} spectrum in the energy range 70–5000 MeV

not agree with this conclusion and prefers time variability of Cyg X-3 to explain the disagreement.

4. Discussion

4.1. Observed spectrum from 10^3 eV to 10^{17} eV

From the discussion of the X-ray and gamma-ray results in the previous sections we can derive a consistent picture of the observed Cyg X-3 spectrum.

Figure 6 shows the power emitted per decade of energy from the keV region up to $\sim 10^{17}$ eV. At the lowest energies the spectrum of White and Holt (1982) has been used as being typical at these energies: strong variability up to ~ 20 keV where the high and low state start to converge and become consistent with the Leimit spectrum, which is representative for the hard X-ray results. Extrapolation of the Leimit spectrum to the gamma-ray energies is consistent with the COS-B upper limits derived for the specified phase intervals. At higher energies, the power emitted in the decade above the energy thresholds is indicated, assuming an E^{-2} spectrum which is consistent with most of the data points. Extrapolation of an E^{-2} spectrum down to the 100 MeV region, however, is not consistent with the COS-B upper limit should the shape of the light curve at these energies be the same as above 10^{12} eV.

4.2. Implications for Cyg X-3 models

The recent detections above 10^{14} eV raised much interest in constructing models for the Cyg X-3 binary system. If the MeV-GeV photons represent the tail of the spectrum which results from the production of the photon energies above 10^{14} eV, then these models should also explain the minimum in Fig. 6.

Eichler and Vestrand (1984, 1985) evaluated the scenario of a young, rapidly rotating pulsar in a binary system, as first suggested by Basko et al. (1974) and further studied for the high-energy output part by Bignami et al. (1977). For a pulsar with a magnetic field of $\sim 10^{12}$ G and rotating with a period of ~ 10 ms [compatible with the ~ 12.59 ms period reported by Chadwick et al. (1985)], they indicate that it is possible to achieve potential gaps near the pulsar sufficient to accelerate ions to energies of $\sim 10^{16}$ eV. In their model these particles interact with the corona of the companion star producing the ultra-high-energy gamma radiation. Hillas (1984) presented calculations based on this model for a monoenergetic spray of 10^{17} eV protons at $\sim 10^{39}$ erg s^{-1}, generating an electron-photon cascade in the environs of the companion star. His calculated photon spectrum represents the measurements satisfactorily down to the TeV range, but an extrapolation down to the MeV-GeV range was not shown. Recent calculations indicated that the integral spectrum below $\sim 10^{14}$ eV is rather flatter ($\propto E^{-0.9}$) than one might expect by simply joining the published 10^{12} eV and 10^{15} eV data, because the latter fluxes are depressed by absorption of 10^{15} eV gamma rays in the microwave flux over the ~ 12 kpc path. The calculated integral flux above 100 MeV is $\gtrsim 10^{-7}$ photons cm^{-2} s^{-1}, close to the COS-B upper limits for the phase intervals in which the gamma rays above 10^{12} eV were detected and below the upper limits for the X-ray light curve (Hillas, private communication). Recently, Kazanas and Ellison (1986) considered diffusive shock acceleration of ions as the mechanism reponsible for the ultra-high-energy

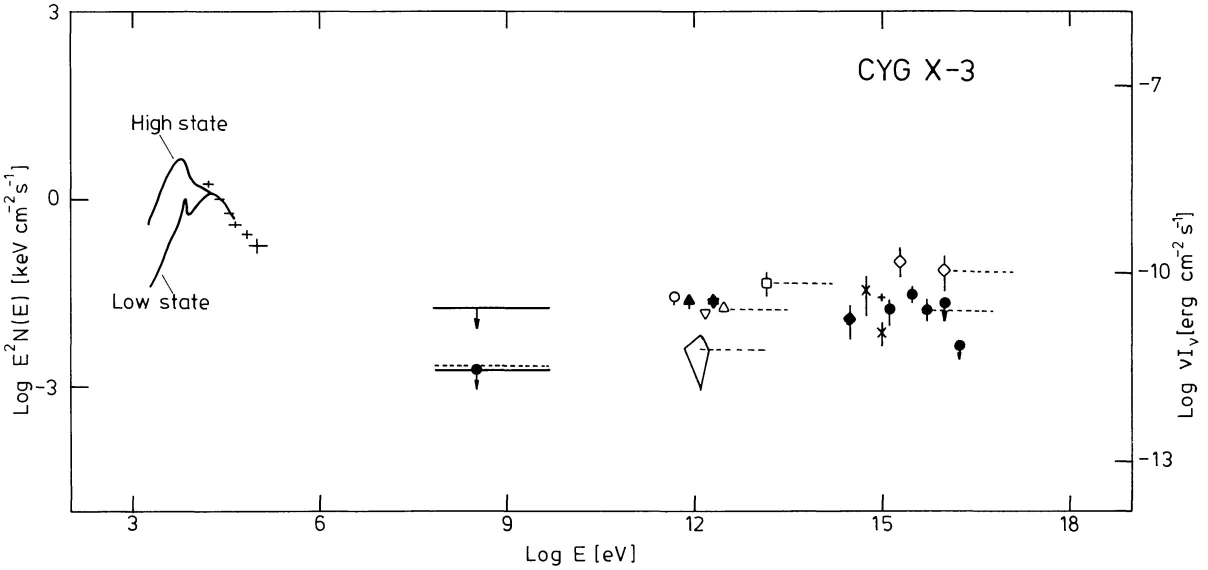

Fig. 6. High-energy spectrum of Cyg X-3, measuring the power per decade of energy; a horizontal line on this plot means there is equal power at all observed decades. Used data from (left to right): — White and Holt (1982); —+— Leimit data; COS-B upper limits for phase intervals in the 4.8 h light curve 0.1–0.9 (—↓—), 0.2–0.3 (—♦—) and 0.5–0.7 (--♦--); ○ Lamb et al. (1982), ▲ Cawley et al. (1985). ◊ Dowthwaite et al. (1983), ▽ Stepanian et al. (1982), ⋆ Danaher et al. (1981) and Neshpor et al. (1979), △ Mukanov et al. (1979), □ Morello et al. (1983), ◆ Alexeenko et al. (1985), × Kifune et al. (1985), + Lambert et al. (1985), ● Lloyd-Evans et al. (1983), ◇ Samorski and Stamm (1983). For the data points at $E > 500$ GeV the values indicate the power emitted over one decade in energy above the threshold energy, assuming an E^{-2} spectrum. The broken lines indicate for some examples the decade in energy over which is integrated

gamma-ray emission from Cyg X-3. In their model only a flux of ultra-high-energy neutrons can escape from the acceleration site because of the high magnetic field ($\gtrsim 10^8$ G). These neutrons produce the gamma radiation in the atmosphere of the binary companion.

Chanmugam and Brecher (1985) propose an alternative model for acceleration of particles to ultra-high-energies in binary systems. The energy source is accretion; they suggest that the high-energy particles, which produce the gamma rays, are accelerated in an accretion disk, which rotates about the neutron star. The particles are accelerated radially outward along electric field lines, which are produced by the magnetic field of the neutron star in the plane of the disk. A fraction of these particles can interact with gas in the atmosphere of the companion star, or much closer to the neutron star with gas in the accretion stream.

4.3. Absorption effects around Cyg X-3

Independent of the actual gamma-ray production mechanism in the Cyg X-3 binary system, absorption effects could significantly change the appearance of the spectrum for the observer, and might account for the minimum in the high-energy gamma-ray domain. Apparao (1984) studied the absorption of 10^{12} eV gamma rays by infrared photons; in addition he found that gamma rays above 10^{15} eV are not affected by the photon field. Around 1 GeV, however, absorption by the abundant soft X-rays might be particularly important, as suggested by e.g. Vestrand (1983). We examined this possibility.

A simple calculation of optical depths, applied to the total primary spectrum, will lead to erroneous results because the gamma rays absorbed are emitted again at lower energy. For the correct treatment one has to solve the transfer equation for photons taking into account absorption and re-emission of gamma rays (Mastichiadis, 1986). In our calculations, an electron-positron cascade is initiated as a primary gamma ray interacts with the X-ray photon field characterized by a luminosity L_X, an energy ε_X and a characteristic size R_*. The processes considered included photon-photon ($\gamma-\gamma$ pair production) and photon-electron (Compton scattering and γ-e pair production) interactions. The photon number density was assumed to be much larger than the particle number density, so processes that involve particle interactions (i.e. bremsstrahlung, e^+/e^- annihilation etc.) could be neglected. The exact cross-sections were used, and particles and gamma rays were traced until they escaped from the system.

We assumed that the X-rays come from an extended region, possibly an accretion disk corona (White and Holt, 1982), and have the spectral distribution shown in Fig. 3. The distribution of the X-rays was taken to be isotropic up to some distance R_* (the coronal radius) from the central source, and to have a $1/R^2$ dependence beyond. We injected a primary gamma-ray spectrum $N(E) \propto E^{-2}$, with $10^6\,\mathrm{eV} < E < 10^{15}\,\mathrm{eV}$ (photons of higher energies would not be able to escape from the strong magnetic field), somewhere close to the central source and calculated the modified spectrum, with R_* as the only free parameter. Figure 7 shows that the resulting spectrum has a clear absorption dip in the 100 MeV to 1 TeV region. The decrease of the absorption depth with increasing R_* can be understood simply because the optical depth is of order $\tau = n_X \sigma_X R_*$ and the ambient photon number density is

$$n_X = L_X / 4\pi R_*^2\, c\varepsilon, \text{ so } \tau \propto R_*^{-1}. \qquad (2)$$

Comparing the theoretical curves with the observed spectrum, we find that if the failure to observe Cyg X-3 with COS-B is to be attributed to the absorption of MeV-GeV gamma rays by the keV photons, one requires that the letter must originate in a region not larger than about 10^{10} cm. This is in rough agreement with the

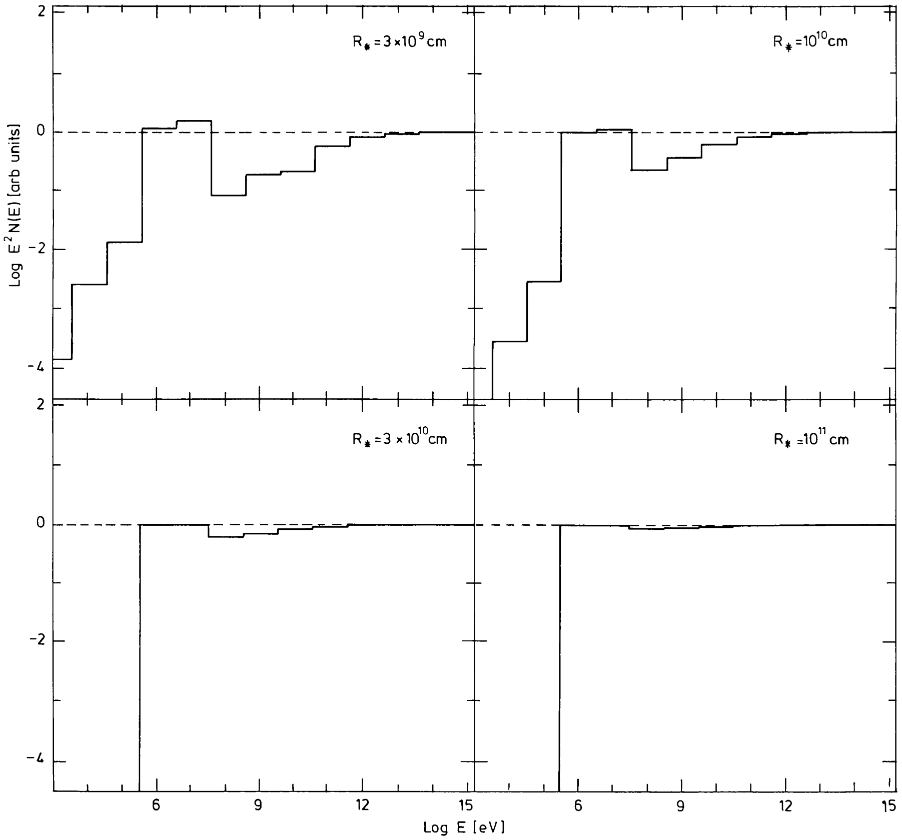

Fig. 7. Calculated high-energy spectra for a primary gamma-ray spectrum $N(E) \propto E^{-2}$ (10^6 eV $< E < 10^{15}$ eV) injected close to the central source in a model of the Cyg X-3 system, and modified because of absorption by soft X-rays which are distributed isotropically up to some distance R_* from the central source (see text). The selected values of R_* are given in the figure

model of White and Holt, in which the accretion disk corona has a radius (1–2) 10^{10} cm.

5. Conclusions

Considering the 14 decades in energy from 1 keV up to $\sim 10^{17}$ eV, the power emitted per decade of energy by Cyg X-3 reaches a minimum in the high-energy gamma-ray domain ($\sim$0.1–5 GeV). If the primary gamma-ray spectrum from this energy range up to the ultra-high energies originates in, or near, an accretion disk corona (e.g. Chanmugam and Brecher, 1985) with radius $\lesssim 10^{10}$ cm, then absorption of gamma-rays by the ambient X-ray photons could explain this phenomenon. If the gamma radiation originates from the interaction of accelerated particles with gas in the atmosphere of the companion star (binary separation of $\sim 10^{11}$ cm) (Vestrand and Eichler, 1982; Chanmugam and Brecher, 1985; Kazanas and Ellison, 1986), such an absorption effect is too small. The calculations by Hillas (1984, and private communication) indicate, however, that a reduction in the emitted power in the MeV-GeV region can be expected.

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