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Observation of Gamma Rays With a 4.8 Hour Periodicity From CYG X-3

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ABSTRACT

Energetic (E > 35 MeV) γ-rays have been observed from Cyg X-3 with the SAS-2 γ-ray telescope. They are modulated at the 4.8^h period observed in the X-ray and infrared regions, and within the statistical error are in phase with this emission. The flux above 100 MeV has an average value of $(4.4 \pm 1.1) \times 10^{-6}$ photons $cm^{-2}s^{-1}$. If the distance to Cyg X-3 is 10 kpcs, this flux implies a luminosity of more than 10^{37} ergs s^{-1} if the radiation is isotropic and about 10^{36} ergs s^{-1} if the if the radiation is restricted to a cone of one steradian, as it might be in a pulsar.

Subject headings: γ-rays, binaries, pulsars, Cygnus X-3.

*On faculty leave from Iowa State University, August 1975-August 1976.

I. INTRODUCTION

Cygnus X-3 is a particularly interesting object for several reasons, including the synchronized 4.8^h modulation of infrared and X-ray emission (Becklin et al., 1973; Mason et al., 1976), the high stability of the 4.8^h X-ray period (Parsignault et al., 1976a), and the erratic, frequency-dependent radio outbursts of up to 2×10^4 times the quiescent flux level with no evidence for a 4.8^h period (cf. Gregory et al., 1972).

In the γ-ray energy range, Galper et al. (1975) reported a 3.6σ excess above 40 MeV of $(2.0 \pm 0.8) \times 10^{-4}$ $cm^{-2}s^{-1}$ from an October 1972 balloon flight, with a 4.8^h modulation in which the minimum γ-ray emission occurred near the time of the X-ray maximum. From balloon flights in September 1972 and July 1973, however, McKechnie, Mount, and Ramsden (1976) report an upper limit to the Cygnus X-3 flux above 70 MeV of 6.5×10^{-6} $cm^{-2}s^{-1}$, well below the result of Galper et al. (1975). Vladimirsky et al. (1975) have reported a positive flux from Cygnus X-3 above 10^{12} eV.

In the course of a search of the SAS-2 γ-ray data for emission from suspected X-ray binaries, strong evidence has been found for radiation from the Cygnus X-3 region in the energy range above 35 MeV. The specific identification with Cygnus X-3 is based on the observation of a 4.8 hr. periodicity in the γ-ray data in phase with the X-ray emission. On the basis of the observed γ-ray flux and a distance estimate of 10 kpc (Laque, Laqueux, and Nguyen-Quant-Rieu, 1972), Cyg X-3 is the most luminous γ-ray point source yet identified by well over an order of magnitude. Upper limits reported in this paper from the other X-ray sources in the survey further distinguish Cyg X-3 from conventional accreting binaries and raise anew the question of the underlying physical characteristics of this object.

The telescope used to collect the data reported here is a 32-level wire-grid, magnetic-core spark chamber assembly covered by an anti-coincidence scintillator and triggered by any one of four independent directional scintillator-Cerenkov counter telescopes in anticoincidence with the outer scintillator (Derdeyn et al., 1972). A general discussion of the data analysis procedure, the experiment calibration, and the detector response is given by Fichtel et al. (1975) and Thompson et al. (1976).

II. RESULTS

The majority of the data used in the Cyg X-3 study came from the observing period 7-13 March 1973 with a small portion from 1-6 March 1973. Figure 1 presents the histogram of γ-ray arrival times for γ-rays from within an error circle of approximately 1.2σ of the direction of Cyg X-3, plotted as a function of phase within the $(0.1996814 \pm 0.0000005)$d period seen in X-rays (Parsignault et al., 1976a). The zero phase is chosen to coincide with the X-ray minimum as defined by Parsignault et al. (1976a). A small correction is included in the histogram in Fig. 1 to take into account the non-uniform exposure to the source as a function of phase resulting from the 4.8^h source period being close to three times the SAS-2 earth orbital period. The probability that the distribution shown in Fig. 1 is random is less than one part in a thousand, and the argument becomes more persuasive when it is noted that the two adjacent low intervals are consistent in intensity level with the celestial and galactic diffuse emission and that the X-ray minimum falls within these two intervals.

The flux from Cyg X-3 averaged over the 4.8^h period is found to be $(4.4 \pm 1.1) \times 10^{-6}$ photons $cm^{-2} sec^{-1}$ for E > 100 MeV and $(10.9 \pm 3) \times 10^{-6}$ photons $cm^{-2} sec^{-1}$ for E > 35 MeV, where the uncertainty includes both statistical and systematic errors.

As noted in the introduction, the γ-ray emission from Cyg X-3 was revealed in a systematic search of the SAS-2 data for radiation from periodic X-ray sources. Table 1 lists all known or suspected binary sources with an intensity greater than 50 UHURU counts/sec. (Giacconi et al. 1974). The last three entries are only considered to be possible binaries. In particular for Cyg X-3, the 4.8^h variation may very well not be orbital in nature, as will be discussed later.

Cyg X-3 is seen to be the only source on the list for which a positive flux of γ-rays was seen. If the distance to Cyg X-3 is 10 kpc, the observed flux value implies that the power emitted in γ-rays with energies above 35 MeV is in excess of 10^{37} ergs s^{-1} if the radiation is isotropic and over 10^{36} ergs s^{-1} if the radiation is restricted to a cone of one steradian as it might be in a pulsar. For comparison, the next most luminous identified γ-ray point source is the Crab pulsar with a radiated γ-ray power above 35 MeV of approximately 6×10^{34} ergs s^{-1}, where the emission is assumed to be uniform within a solid angle of 1 sr.

The differential γ-ray flux is shown in Fig. 2 together with measurements in the radio, infrared, and X-ray energy intervals.

Table I

Source	Observed Periods	UHURU Intensity[1] (ct/sec)	γ-Ray Flux[4] $10^5 \times \gamma$'s(E>100 MeV)$cm^{-2}s^{-1}$
3U 1700-37	3.4^d	102	< 1.0 (3.4^d)
3U0900-40 (Vela XR-1)	283^s 9.0^d	100	< 0.8 (9.0^d)
Her X-1	1.2^s 1.7^d 35.0^d	100	< 0.5
SMC X-1	0.7^s 3.9^d	78	< 0.7
Cen X-3	4.8^s 2.1^d	160	< 2.5[3]
Cyg X-1	5.6^d	1176	< 1.1
Sco X-1	0.8^d	17000	< 1.0[2]
Cyg X-2	13.6^d	540	< 1.2[2]
Cyg X-3	4.8^h	194	4.4 ±1.1

1. Giacconi et al. 1974.
2. Fichtel et al. 1975
3. The relatively high upper limit is due to the source being near the edge of the field of view and in the galactic plane.
4. If the upper limit applies to a specific period, it is given in parenthesis; otherwise, the upper limit applies to the time averaged flux.

Although it is tempting to draw a smooth curve through these data, it must be remembered that the radio emission is highly variable, and a wide variation in X-ray spectra has been observed, including the identification of X-ray emission lines superimposed on a hard continuum at some times and consistency with a black-body distribution at others (Serlemitsos et al. 1975). Thus, as will be discussed in the next section, the origin of the radiation in different parts of the spectrum may be quite different.

III. DISCUSSION

As noted in the in the introduction, there is also a 4.8^h modulation seen in the infrared region which is apparently only present at some times and not others (Mason et al. 1976). In general, when the modulation is present in the infrared, its amplitude is significantly less than that seen in X-rays. On the other hand the modulation of the γ-rays as seen in Fig. 1 is nearly complete, indicating a possible natural progression in the amplitude of the modulation as the energy of the radiation increases. The absence of any detectable radio modulation reported by Mason et al. (1976) is consistent with this characteristic. This feature may indicate a progression in the size of the emitting region as the energy changes, with the highest energy γ-rays originating from the smallest volume of space.

The shape of the γ-ray modulation above the lowest intensity level is consistent with the shape as seen in X-rays (Mason et al. 1976). The minimum in the γ-ray distribution occurs from 0.9 to 0.3

in phase. The observations of Parsignault et al (1976b) show that in the phase interval from 0.85 to 0.25 the X-ray intensity has its lowest values and shows little variation. (Note: Add .25 to the phase used by Parsignault et al. to obtain that used here.) Except for a difference in phase of 0.05 which could easily be a statistical fluctuation in the γ-ray data, the γ-ray emission, therefore, would seem to correspond with the period in which X-ray variability was seen.

The mechanism for producing the γ-rays is uncertain. Binary models which have been proposed for X-ray emission include those in which there is a smaller object, either a white dwarf (e.g. Davidsen and Ostriker, 1974) or a neutron star (e.g. Shklovsky, 1967; Pringle, 1974) and one in which the observed X-rays are those reflected off the large companion star (Basko, Sunyaev, and Titarchuk, 1974). The extension of most of these models to include γ-ray emission is generally difficult. Accretion onto either a white dwarf or a neutron star as the source of γ-rays seems unlikely, both in view of absence f γ-rays from the other entries in Table 1 and the energy required to produce the γ-rays. Other difficulties associated with binary hypotheses for Cyg X-3 include the very clear and apparently unchanging asymmetric nature of the X-ray phase plot and the rather small separation of the centers of the two objects dictated by the length of the observed period unless at least one of the objects is quite massive.

Accretion onto a black hole has also been proposed as a source of γ-ray (Dahlbacka, Chapline, and Weaver 1974); however, the total energy in γ-rays observed here is very much larger than that predicted for this process.

If the previous SAS-2 results on localized γ-ray sources (Thompson et al. 1975; Ögelman et al. 1976; Thompson et al. 1976) are used to suggest possibilities, then a pulsar origin would seem to be a likely possibility. Four pulsars are now known to emit γ-rays and the possibility that Cyg X-3 is a fifth certainly exists. It should be emphasized that it seems quite unlikely that the 4.8^h period is the one to be associated with the pulsar since all known radio pulsars have periods of several seconds or less, and also a much larger period than those observed would imply a much smaller rate of energy emission. Pursuing the pulsar possibility, Treves (1973) has proposed that the 4.8^h period is a free precession of the spin axis of a neutron star, and, on this basis, he predicts that the rotation period of the neutron star would be approximately 13 msec. A search of the radio emission from Cyg-3 for a pulsar in this period range would be desirable despite the dispersion and low flux problems associated with the large distance.

Another possible model is one in which a young pulsar is part of a binary system. Again, the γ-ray emission might be associated with the pulsar itself. Detection of a radio counterpart would be even more difficult in this case due to absorption by the plasma in the source region. In this model in particular, the X-ray and infrared emission may very well have a different origin, for example, accretion onto the neutron star. On the basis of the other γ-ray sources observed and these last two models, the fast pulsar possibility seems to deserve serious attention as a candidate for explaining the γ-ray emission from Cyg X-3.

ACKNOWLEDGMENTS

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FIGURE CAPTIONS

Fig. 1 - Distribution of γ-ray arrival times in fractions of the (0.1996814 ±.0000005)d period for γ-rays above 35 MeV from the region of Cygnus X-3. The zero of time corresponds to the X-r minimum defined by Parsignault et al. (1976a) dashed portions of the plot are repeated parts of the single period distribution, shown to emphasize the periodicity. The dotted lines show the number of γ-rays normalized to the average SAS-2 exposure to Cyg X-3. The dot-dashed line shows the estimated contribution from diffuse celestial and galactic radiation, together with its uncertainty.

Fig. 2 - The differential photon energy flux spectrum observed for Cygnus X-3. Upward pointing arrows on the radio fluxes indicate that flaring sometimes increases these fluxes by over an order of magnitude. The X-ray intensities are represented by cross-hatched regions which bracket the reported values. The radio observations show no indication of the 4.8^h pulsation; however, at higher frequencies there is a pulsed component which apparently increases relative to the constant component as a function of energy.

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FIGURE 1

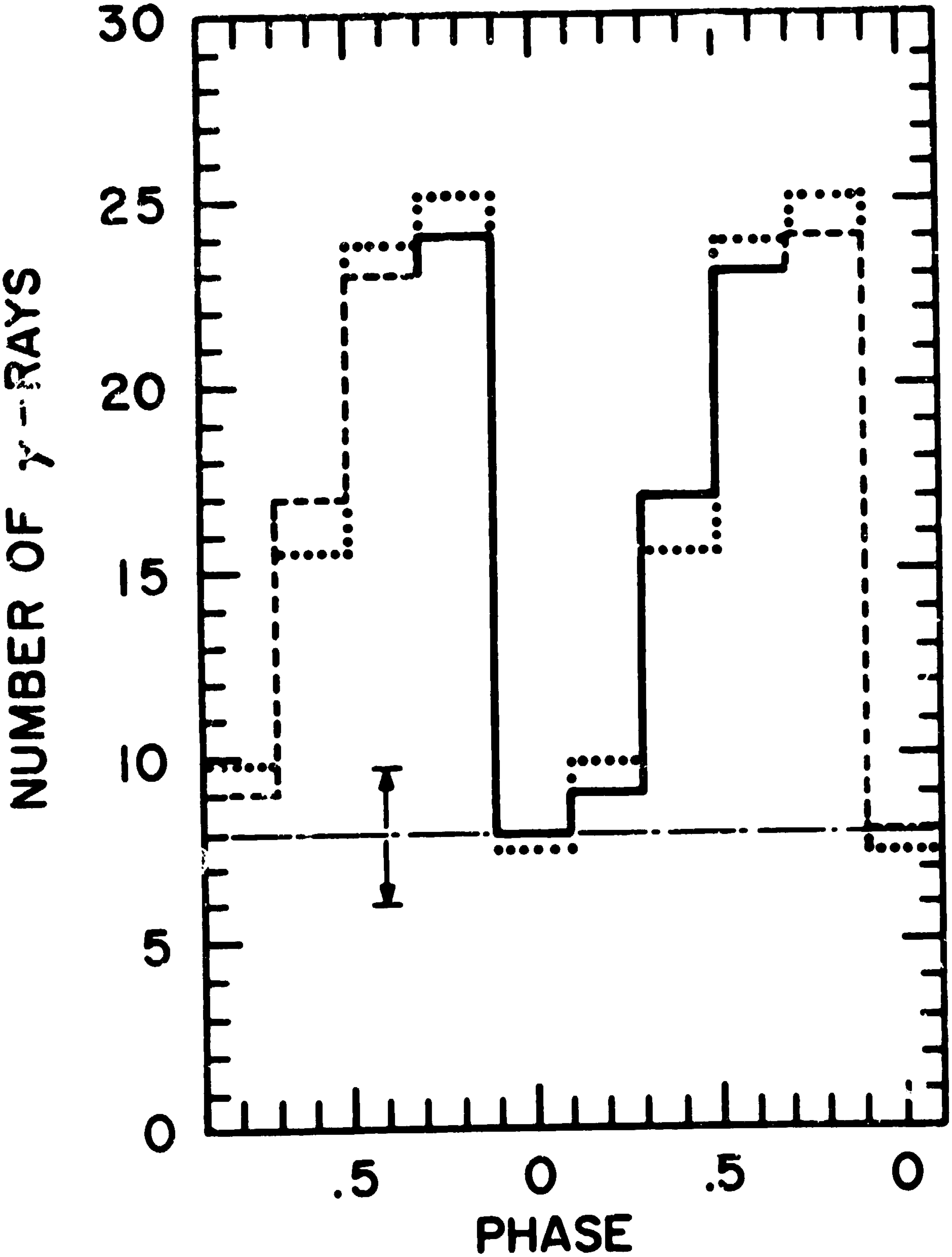

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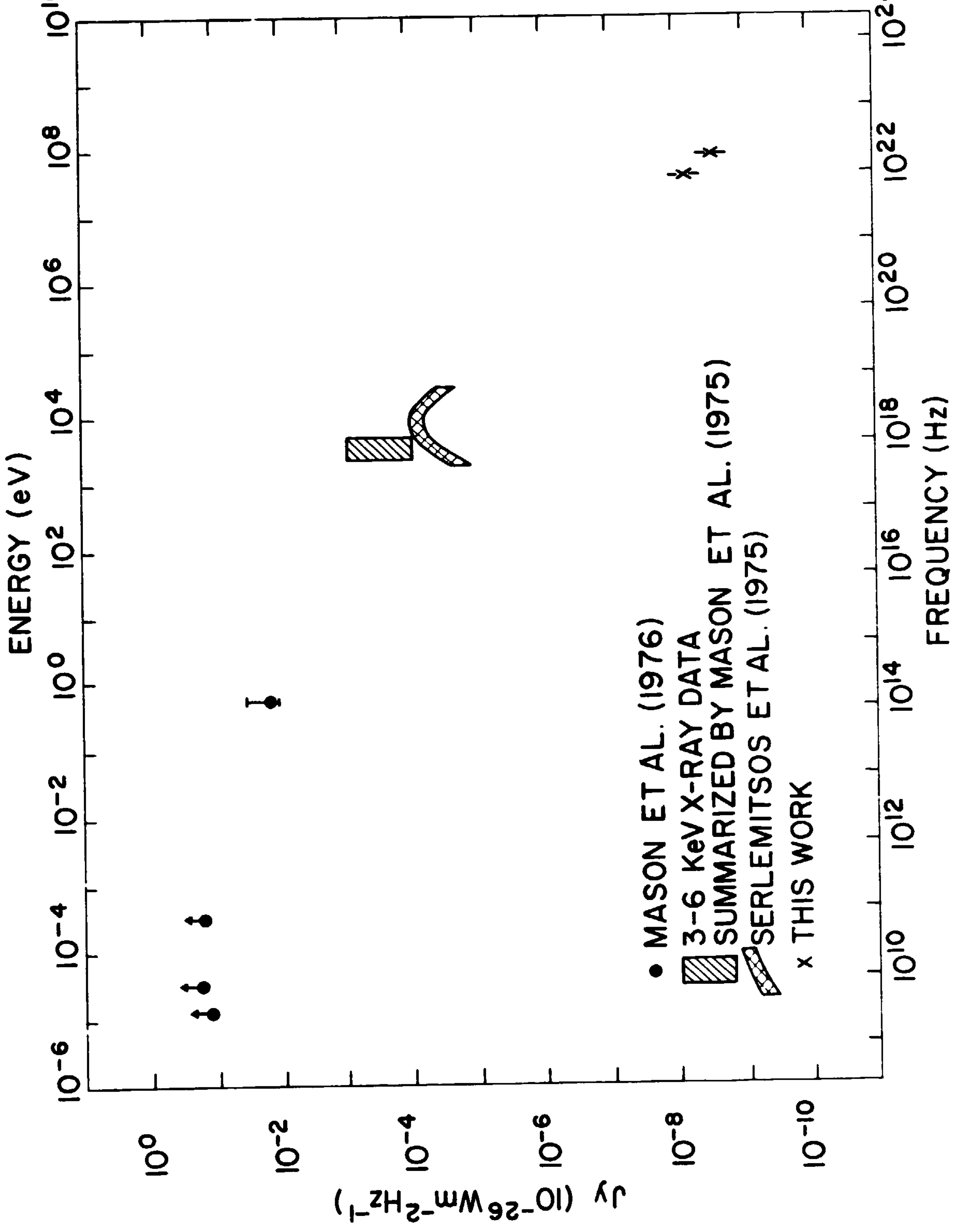
FIGURE 2



ENERGY (eV)
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
10^{10}
FREQUENCY (Hz)
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
10^{22}
10^{24}
Jy (10^{-26} Wm^{-2}Hz^{-1})
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
• MASON ET AL. (1976)
3–6 KeV X-RAY DATA SUMMARIZED BY MASON ET AL. (1975)
SERLEMITSOS ET AL. (1975)
x THIS WORK