THE ASTROPHYSICAL JOURNAL, 212:L63–L66, 1977 March 1

OBSERVATION OF GAMMA RAYS WITH A 4.8 HOUR PERIODICITY FROM CYGNUS X-3

R. C. LAMB,* C. E. FICHTEL, R. C. HARTMAN, D. A. KNIFFEN, AND D. J. THOMPSON
NASA/Goddard Space Flight Center, Greenbelt, Maryland 20771
Received 1976 September 8; revised 1976 November 9

ABSTRACT

Energetic ($E > 35$ MeV) γ-rays have been observed from the direction of Cygnus X-3 with the SAS-2 γ-ray telescope. The statistical significance of the excess above the galactic and diffuse radiation is approximately 4.5 σ. In addition, the γ-ray flux is modulated at the $4^{h}.8$ period observed in the X-ray and infrared regions, and within the statistical error is 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 Cygnus X-3 is 10 kpc, 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 radiation is restricted to a cone of 1 steradian, as it might be in a pulsar. Upper limits are presented for the γ-ray flux from other known or suspected periodic X-ray sources.

Subject headings: gamma rays: general — pulsars — X-rays: binaries

I. INTRODUCTION

Cygnus X-3 is a particularly interesting object for several reasons, including the synchronized $4^{h}.8$ modulation of infrared and X-ray emission (Becklin *et al.* 1973; Mason *et al.* 1976), the high stability of the $4^{h}.8$ X-ray period (Parsignault *et al.* 1976*a;* Pietsch *et al.* 1976), and the erratic, frequency-dependent radio outbursts of up to 2×10^{4} times the quiescent flux level with no evidence for a $4^{h}.8$ period (cf. Gregory *et al.* 1972).

In the γ-ray energy range, Galper *et al.* (1975) reported a 3.6 σ excess above 40 MeV of $(2.0 \pm 0.8) \times 10^{-4}$ cm^{-2} s^{-1} from a 1972 October balloon flight, with a $4^{h}.8$ modulation in which the minimum γ-ray emission occurred near the time of the X-ray maximum. A 1974 July flight by this same group failed to confirm this result. From balloon flights in 1972 September and 1973 July, 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 Cyg 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 Cyg X-3 region in the energy range above 35 MeV. The specific identification with Cyg X-3 is based on the observation of a $4^{h}.8$ 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, by well over an order of magnitude, the most luminous γ-ray point source yet identified. Upper limits reported in this *Letter* 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 anticoincidence 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.* (1977).

II. RESULTS

The Cyg X-3 source was about 20° from the SAS-2 detector axis (FWHM response angle ~35°) for 62 continuous orbits between 1973 March 1 and 6, and about 12° from the axis for 105 continuous orbits between 1973 March 6 and 13. Except for half of each orbit, when the source was occulted by the Earth, and small data losses, SAS-2 monitored Cyg X-3 for over 50 of its $4^{h}.8$ periods. Based on the observed emission from the surrounding regions of the galactic plane, the expected photon count from within a 1.2 σ error circle of Cyg X-3 would be 39 ± 9 photons ($E > 35$ MeV). The actual number observed was 81, or about a 4.5 σ excess. Although they do not affect the statistical significance, the exposure factor and detector efficiency calibration introduce an additional uncertainty in converting the photon number excess to a photon flux. The time-averaged flux from Cyg X-3 is found to be $(4.4 \pm 1.1) \times 10^{-6}$ photons cm^{-2} s^{-1} for $E > 100$ MeV and $(10.9 \pm 3.1) \times 10^{-6}$ photons cm^{-2} s^{-1} for $E > 35$ MeV. This result falls below the upper limit of McKechnie, Mount, and Ramsden (1976). The 3.6 σ excess seen by Galper *et al.* (1975) lies more than an order of magnitude above either the SAS-2 result or the balloon upper limit.

Figure 1 presents the histogram of γ-ray arrival times

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

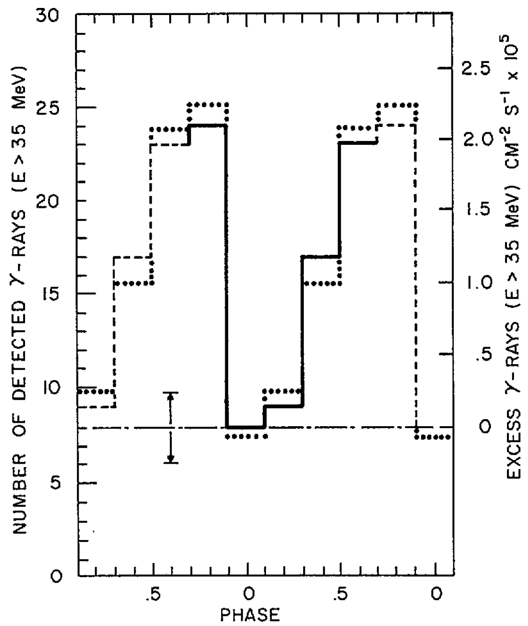

FIG. 1.—The solid line shows the distribution of arrival times of all detected γ-rays ($E > 35$ MeV) from the region of Cyg X-3 in fractions of the ($0^{d}1996814 \pm 0^{d}0000005$) period. The zero of time corresponds to the X-ray minimum defined by Parsignault *et al.* (1976). Dashed portions of the 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. The scale on the right shows the conversion of the excess to photon flux, which contains an additional systematic uncertainty of about 10%.

for γ-rays within an error circle of approximately 1.2 σ of the direction of Cyg X-3, plotted as a function of phase within the ($0^{d}1996814 \pm 0^{d}0000005$) period seen in X-rays (Parsignault *et al.* 1976). The zero phase is chosen to coincide with the X-ray minimum (JD 2,440,949,9176) used by Parsignault *et al.* (1976). Because the $4^{h}8$ period is close to 3 times the SAS-2 orbital period, the SAS exposure to the source as a function of its phase is not quite uniform. The correction to the number of photons for this nonuniformity is small, as can be seen in Figure 1, and the uncertainty in the correction is much smaller than the correction itself. At least 99% of the uncertainty in this histogram, then, is determined by the counting statistics, which are directly visible in the figure. The probability of observing the distribution shown in Figure 1 if no time variation is present 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. This observed modulation of the γ-ray flux is strong evidence that the γ-ray source is physically associated with Cyg X-3.

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 s^{-1} (Giacconi *et al.* 1974). The last three entries are only considered to be possible binaries. In particular for Cyg X-3, the $4^{h}8$ variation may very well not be orbital in nature, as will be discussed later.

Cygnus 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 1 sr 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 Figure 2 together with measurements in the radio, infrared, and X-ray energy intervals. 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 superposed on a hard continuum at some times and consistency with a blackbody distribution at others (e.g., 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.

TABLE 1

BINARY X-RAY SOURCES

Source	Observed Periods	*Uhuru* Intensity[a] (counts s^{-1})	γ-Ray Flux[b] in Units of 10^{-6} γs' ($E > 100$ MeV) cm^{-2} s^{-1}
3U 1700−37	$3^{d}4$	102	<1.0 ($3^{d}4$)
3U 0900−40 (Vela XR-1)	283^{s} $9^{d}0$	100	<0.8 ($9^{d}0$)
Her X-1	$1^{s}2$ $1^{d}7$ $35^{d}0$	100	<0.5
SMC X-1	$0^{s}7$ $3^{d}9$	78	<0.7
Cen X-3	$4^{s}8$ $2^{d}1$	160	<2.5[c]
Cyg X-1	$5^{d}6$	1176	<1.1
Sco X-1	$0^{d}8$	17000	<1.0[d]
Cyg X-2	$13^{d}6$	540	<1.2[d]
Cyg X-3	$4^{h}8$	194	4.4 ± 1.1

[a] Giacconi *et al.* 1974.

[b] If the upper limit applies to a specific period, it is given in parentheses; otherwise, the upper limit applies to the time-averaged flux.

[c] The relatively high upper limit is due to the source being near the edge of the field of view and in the galactic plane.

[d] Fichtel *et al.* 1975.

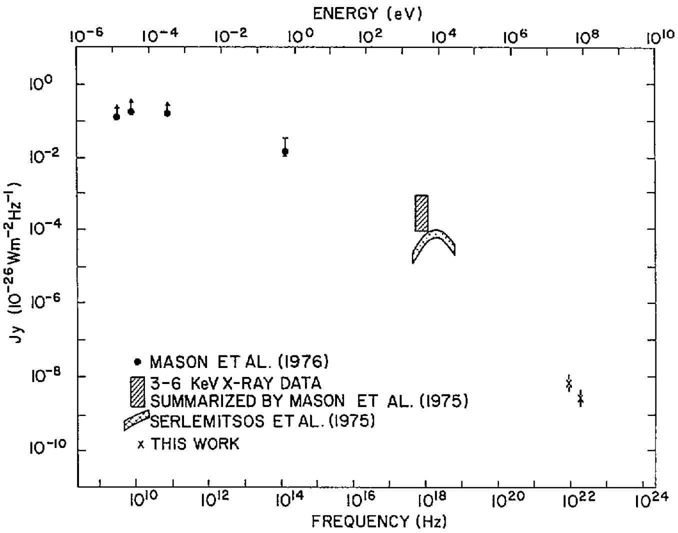

FIG. 2.—The differential photon energy flux spectrum observed for Cyg X-3. Upward pointing arrows on the radio fluxes indicate that flaring sometimes increases these fluxes by over an order of magnitude. The X-ray intensities are represented by crosshatched regions which bracket the reported values. The radio observations show no indication of the $4^h.8$ periodicity; however, at higher frequencies there is a periodic component which apparently increases relative to the constant component as a function of energy.

III. DISCUSSION

As noted in the Introduction, there is also a $4^h.8$ modulation seen in the infrared region which is apparently not present at all times (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 Figure 1 is nearly complete, indicating a possible 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 generally seen in X-rays when many cycles are summed, i.e., a slow rise followed by a rapid decay (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.* (1977) 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 0.25 to the phase used by Parsignault *et al.* [1977] 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., Shlovsky 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 the absence of γ-rays from the other entries in Table 1 and the energy required to produce the γ-rays. Other possible difficulties associated with binary hypotheses for Cyg X-3 include the 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-rays (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; Ogelman *et al.* 1976; Thompson *et al.* 1977) 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 should be considered. It should be emphasized that it seems quite unlikely that the $4^h.8$ 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 $4^h.8$ 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 mŝ. 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 might be even more difficult in this case because of 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.

We are happy to acknowledge the helpful discussions that we have had with Elihu Boldt and Joseph Taylor.

REFERENCES

Basko, M. M., Sunyaev, R. A., and Titarchuk, L. G. 1974, *Astr. Ap.*, **31**, 249.
Becklin, E. E., Neugebauer, G., Hawkins, F. J., Mason, K. O., Sanford, P. W., Matthews, K., and Wynn-Williams, C. G. 1973, *Nature Phys. Sci.*, **245**, 302.
Dahlbacka, G. H., Chapline, G. F., and Weaver, T. A. 1974, *Nature*, **250**, 36.
Davidsen, A., and Ostriker, J. P. 1974, *Ap. J.*, **189**, 331.
Derdeyn, S. M., Ehrmann, C. H., Fichtel, C. E., Kniffen, D. A., and Ross, R. W. 1972, *Nucl. Instr. Methods*, **98**, 557.
Fichtel, C. E., Hartman, R. C., Kniffen, D. A., Thompson, D. J., Bignami, G. F., Ögelman, H., Özel, M. E., and Tümer, T. 1975, *Ap. J.*, **198**, 163.
Galper, A. M., Kirillov-Ugryumov, V. G., Kurochkin, A. V., Leikov, N. G., Luchkov, B. I., and Yurkin, Yu. T. 1975, *Proc. 14th International Cosmic Ray Conference*, Munich, Vol. **1**, p. 95.
Giacconi, R., Murray, S., Gursky, H., Kellogg, E., Schreier, E., Matilsky, T., Koch, D., and Tananbaum, H. 1974, *Ap. J. Suppl.*, No. 237, **27**, 37.
Gregory, P. C., Kronberg, P. P., Seaquist, E. R., Hughes, V. A., Woodsworth, A., Viner, M. R., Retallack, D., Hjellming, R. M., and Balick, B. 1972, *Nature Phys. Sci.*, **239**, 114.
Laque, R., Lequeux, J. and Nguyen-Quant-Rieu. 1972, *Nature Phys. Sci.*, **239**, 120.
Mason, K. O., Becklin, E. E., Blankenship, L., Brown, R. L., Elias, J., Hjellming, R. M., Matthews, K., Murdin, P. G., Neugebauer, G., Sanford, P. W., and Willner, S. P. 1976, *Ap. J.*, **207**, 78.
Mason, K. O., Sanford, P., and Ives, J. 1975, *GSFC X-Ray Binary Symposium* (NASA SP-389), p. 255.
McKechnie, S. P., Mount, K. E., and Ramsden, D. 1976, *Ap. J. (Letters)*, **207**, L151.
Ögelman, H. B., Fichtel, C. E., Kniffen, D. A., and Thompson, D. J. 1976, *Ap. J.*, **209**, 584.
Parsignault, D. R., Grindlay, J., and Gursky, H. 1977, *Ap. J.* (Letters), in press.
Parsignault, D. R., Schreier, E., Grindlay, J., and Gursky, H. 1976, *Ap. J. (Letters)*, **209**, L73.
Pietsch, W., Kendziorra, E., Staubert, R., and Trumper, J. 1975, *Ap. J. (Letters)*, **203**, L67.
Pringle, J. E. 1974, *Nature*, **247**, 21.
Serlemitsos, P. J., Boldt, E. A., Holt, S. S., Rothschild, R. E., and Saba, J. L. R. 1975, *Ap. J. (Letters)*, **201**, L9.
Shklovsky, I. S. 1967, *Ap. J. (Letters)*, **148**, L1.
Thompson, D. J., Fichtel, C. E., Hartman, R. C., Kniffen, D. A., and Lamb, R. C. 1977, *Ap. J.*, in press.
Thompson, D. J., Fichtel, C. E., Kniffen, D. A., and Ögelman, H. B. 1975, *Ap. J. (Letters)*, **200**, L79.
Treves, A. 1973, *Nature Phys. Sci.*, **242**, 121.
Vladimirsky, B. M., Neshpor, Yu. I., Stepanian, A. A., and Fomin, V. P., 1975, *Proc. 14th International Cosmic Ray Conference*, Munich, Vol. **1**, p. 118.

C. E. FICHTEL: Code 660, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

D. A. KNIFFEN, R. C. HARTMAN, and D. J. THOMPSON: Code 662, NASA/Goddard Space Flight Center, Greenbelt, MD 20771

R. C. LAMB: Physics Department, Iowa State University, Ames, IA 50011